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13. ABSTRACT *(Maximum 200 words)*

This midterm report describes work performed during the first year of a two-year SBIR Phase II effort to conduct advanced development of a self-contained suite of sensors capable of measuring, storing, and downloading upon command selected environmental temperature parameters. The sensor suite is being developed to provide the measurement of four environmental parameters (i.e., ambient temperature, relative humidity, windspeed, and radiant energy) in a form suitable for use as input to heat-strain predictive models (an immediate application of the sensor suite is as a miniature sensor for WBGT parameters or for advanced models currently under development by the Army and others). Emphasis during the first year's effort has been placed on maintaining the required levels of precision, accuracy, and reliability in the measurements taken---while achieving desired reductions in unit cost, weight, size, and power consumption through the development of innovative design and packaging concepts, the application of system modularity, the identification and integration of cost-effective off-the-shelf components, and the incorporation of recent advances in electronics. Effort during the second year of this program will be devoted to continued refinement of power and cost/size reduction strategies (particularly as related to windspeed and mean radiant temperature); brassboard, breadboard and prototype fabrication; and validation testing.

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Robert L. Talley 1/25/95

Robert L. Talley, PI — Date

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1. INTRODUCTION

1.1 Nature of the Problem

Defense downsizing, troop-strength reductions, the reformulation of fighting doctrines in response to the end of the Cold War, and a growing emphasis in the Pentagon on dual use and operations other than war[1] have all underscored the need for smaller, better trained, and more mobile fighting units capable of achieving mission objectives rapidly, reliably, and cost effectively. The reality of the chemical/biological threat simultaneously dictates a need for a high level of individual protection equipment, which can bring with it problems associated with equipment interference and individual performance degradation.

Heat stress is a significant contributor to both non-battle injuries and performance degradation, particularly in hostile environments requiring protective attire. The U.S. Army is currently addressing a variety of issues associated with heat injury under the U.S. Army Chemical School's P^2NBC^2 program. P^2NBC^2 is an acronym for the Physiological and Psychological Effects of the NBC Environment and Sustained Operations on Systems in Combat. Of particular interest has been the impact of heat stress on the performance of soldiers attired in MOPP (Mission Oriented Protective Posture) chemical protection.

Work conducted under the P^2NBC^2 program has indicated general agreement between observed physiological response to heat stress and results predicted from the P^2NBC^2 Heat-Strain Decision Aid (HSDA). This decision aid has its foundation in the databases, predictive algorithms, and heat-strain prediction modelling efforts performed by the U.S. Army Research Institute of Environmental Medicine (USARIEM) and others over the past two decades.[2,3,4] Recent field studies and model validation efforts indicate that model performance generally improves with the quality of meteorological inputs.

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[1] *"HASC [House Armed Services Committee] Members Encourage Dual Use for Law Enforcement as Authorization Bill Goes to Conference," Technology Transfer Week, July 26, 1994, Vol. 1, No. 25. p. 1-2.*

[2] *W.R. Santee, W.T. Matthew, and W.J. Tharion, "Simulated Approach Marches During Thermal Stress: a P^2NBC^2 Study," US Army Research Institute of Environmental Medicine, Natick, MA 01750-5007, Technical Report No. T12-92, September 1992.*

[3] *Kent B. Pandolf, Kent B. et al., "Prediction Modelling of Physiological Responses and Human Performance in the Heat," Comput. Bio. Med., Vol 15 No. 5, p. 319-329, 1986.*

[4] *Kenneth K. Kraning II, "A Computer Simulation for Predicting the Time Course of Thermal and Cardiovascular Responses to Various Combinations of Heat Stress, Clothing, and Exercise," U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760-5007, Technical Report No. T13-91, June 1991.*

indicate that model performance generally improves with the quality of meteorological inputs.

The importance of temperature as a contributing factor to worker performance and productivity has long been recognized (as indicated by the incorporation of the WBGT approach in ISO Standard 7726 [5]). One immediate application of the miniature sensor suite under development is to quantify WBGT parameters.

1.2 Purpose of the Present Work

The specific purpose of the present SBIR program is to generate a compact sensor suite capable of measuring and downloading on demand (for computational purposes) four basic meteorological input parameters: air temperature, humidity, wind speed and radiant energy.

1.3 Background of Previous Work

The adverse impact of heat stress on human performance has long been recognized. Since the early part of the 20th century, researchers have approached the difficulty of dealing with the multiplicity of variables that contribute significantly to the heat-stress problem from a variety of perspectives :

- Absolute physical standards
- Instrumentation standards
- Statistical sampling techniques
- Consensus derived from experimental data or field experience
- Consensus based only on expert opinion.

HEAT IMPAIRS MARKSMANSHIP

"The solider who is required to fire a rifle under a chemical threat in a sustained operation has a number of stressors which are likely to affect his success. The effects of heat, clothing, and exercise state can have profound effects on marksmanship performance. Heat impairs marksmanship accuracy due to degradation of muscular control (Johnson and Kobrick, 1988). Furthermore, it has been shown that soldiers exercising in the heat that lost the greatest amount of body weight or who did not rehydrate fully, had the most severe decrements to rifle marksmanship accuracy (Tharion, et al., 1989).

W.R. Santee, et al.. September 1992.

[5] *International Standard (ISO) 7726, "Thermal Environments-Instruments and Methods for Measuring Physical Quantities," First Edition-1985-07-01, UDC 331. 043.6:53.08. Reference No. ISO7726-1985(E).*

1.3.1 Heat Strain

Goldman provides a chronological list of indices striving to achieve a numerical expression integrating the various factors contributing to heat stress that dates to 1905.[6]

Each index attempts to provide a decision aid to be used for the purpose of limiting the duration of exposure, reducing the level of work allowed, or requiring that the worker meet certain standards of heat acclimation and/or fitness. Methodologies employed include:

1. Physical indices based on one or more of the physical factors of the environment (humidity, temperature, air motion, and radiant load);
2. Subjective indices based on assessments of thermal sensation;
3. "Rational" indices based on the human heat balance equations; or
4. Physiological indices based on physiological strain (e.g., percent sweated area, predicted rectal temperature, predicted heart rate, etc.).

The first three approaches are based on the capacities or demands for heat transfer of the environment (occasionally adjusted for heat production demanded of the worker but with few adjustments for clothing or work).

Professional research performed since the early 1970s has introduced the importance of the capacities of the work force (as modified by acclimation, hydration, physical fitness, clothing, etc.). Goldman concluded in the late 80s that

> "...the most promising approach for resolution of heat stress problems is through prediction modelling. Such modelling can build on the concept that heat stress results from an imbalance between the demands imposed on the worker by the task and the environment, and the worker's capacity to eliminate the heat load as modified by clothing."[7]

Building on this approach, researchers at USARIEM have made significant progress toward establishing a data base and developing a series of predictive equations for

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[6] *Ralph F. Goldman, "Standards for Human Exposure to Heat," in Environmental Ergonomics, Sustaining Human Performance in Harsh Environments, Edited by Igor B. Mekjavic, Eric W. Banister, and James B. Morrison (Philadelphia: Taylor & Francis, 1988), p. 99-104.*

[7] *op. cit., p.100.*

deep body temperature, heart rate, and sweat loss responses of clothed soldiers performing physical work at various environmental extremes in recent years.[3,4,8]

1.3.2 Sensor Suites

Significantly less work has been devoted, however, to the development of a small, compact, low-cost sensor suite capable of acquiring and reporting meteorological data in real time, and suitable for incorporation into a hand-held environmental monitoring system. An initiative has been undertaken by USARIEM to develop individual heat-stress monitors that could be used to provide an immediate, local measurement of environmental conditions for direct input into the heat strain prediction model.

The standard sensor suites have used a black globe that is 15 cm in diameter for the measurement of sky radiation (T_g). IST manufactures WBGT monitoring instrumentation that uses a black globe that is 1-5/8 inches in diameter. The measured globe temperature (T_{IST}) is then used to calculate the standard black globe temperature (T_g) according to the following:

$$T_{IST} = \frac{2}{3} T_g + \frac{1}{3} T_a \qquad \textbf{(1)}$$

T_a = Temperature-air
T_g = Temperature - 15-cm BLK globe
T_{IST} = Temperature - IST BLK globe.

The IST sensor suite is relatively large and requires a water reservoir for measuring natural relative humidity. A miniaturized sensor suite is not commercially available.

Technical issues and objectives identified early in the Phase II program included the need to:

- Reduce unit size, weight, and cost
- Reduce power requirements (both to extend useful life and to minimize size and weight)
- Minimize sensor interference (with each other and with the main body of the unit)
- Provide ease of maintenance and logistical support (via interchangeablity or modularity, incorporation of readily available off-the-shelf components, etc.).

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[8] *Gerald P. Krueger, Donna T. Cardinal, and Marie E. Stephens, "Publications and Technical Reports of the United States Army Research Institute of Environmental Medicine, 1961-1992," 30 September 1992.*

A critical element of the Phase II effort was the selection and/or development of sensors. The contract specifically precluded the elaborate development of an air temperature sensor since several viable candidates were available as commercial, off-the-shelf equipment.

Designing a sensor suite capable of simultaneously meeting these goals has required the evolutionary development of a series of innovative integration, packaging, and electronic support concepts to permit functional and performance objectives to be met.

1.4 Methods of Approach

Veritay has adopted a systems approach to generate a small (i.e., nominally the size of a cigarette pack), lightweight (i.e., about 100 grams), battery-operated, sensor suite capable of measuring four basic environmental parameters: air temperature, humidity, wind speed, and radiant energy.

Recent technological advances (e.g., chip technology) and state-of-the-art, off-the-shelf components have been identified and appraised for suitability to meet desired sensor suite design goals and requirements, such as configuration, operation non-interference among sensors, electronics, system support and size/weight/power limitations. It has been the goal of this approach to generate a system exhibiting the following characteristics:

- 72-hour mission life
- Display for local presentation of data
- RS232 port for downloading data from most recent run
- Modularity
- Suitability for hand-held or desk-top operation (individual or group use).

Effort during the first year of this two-year program has been devoted to:

1. Identifying and allocating system requirements and goals to system architecture elements;

2. Evaluating currently available off-the-shelf sensing technologies and components;

3. Determining if new technologies or sensor configurations had to be developed to achieve program objectives;

4. Designing and developing integrated sensor modules consistent with size/weight/power/cost goals; and

5. Generating conceptual configurations capable of accommodating performance objectives within the constraints imposed by sensor operation, non-interference requirements, electronic requirements, system support requirements, and size/weight/power limitations.

Initial testing of sensor elements/modules has been undertaken in support of the design effort.

During the second year, individual subsystems will be breadboarded and integrated into prototype configurations for brassboard and prototype testing and evaluation, culminating in the delivery of a validated prototype unit of the sensor suite.

1.5 Understanding the Problem

1.5.1 Heat Stress and the Dynamic Thermal Environment

Heat tolerance problems may arise from a variety of physiological and environmental factors that act independently or interactively to affect the balance of heat production or loss experienced by an individual. The former includes metabolic heat production, heat input from environmental sources, and the rate of physical work; whereas the latter includes the rate of water intake and favorable opportunities for heat exchange with the environment. In particular, protective clothing inhibits both insensible (evaporative) and sensible (convective, conductive, and radiative) heat exchange. When body heat exceeds cooling capability (because of environmental, clothing, task, and/or physical/physiological variables), increased core temperatures can generate performance degradation, unconsciousness, or even death.

In 1988 Goldman identified the following as key factors influencing the heat tolerance of individuals and identified predictive modeling as the methodology having the best potential for resolving the large number of variables involved:

- Environmental parameters (air temperature, humidity, motion, and radiant temperature);
- Clothing parameters (insulation, moisture permeability and pumping coefficient);
- Task variables (load weight, placement or lift, and frequency, speed of movement, terrain and grade); and
- Physical and physiological variables of the worker (weight, surface area, age, physical fitness, level of acclimatization, state of hydration).

Significant advances in database generation and predictive algorithm development have occurred in the wake of Goldman's observations. The next level of model refinement may be dependent to a significant extent on achieving an improved understanding the dynamic nature of the thermal environment (i.e., air temperature, humidity, wind speed, and radiant energy) as it impacts human performance.

1.5.2 Measuring the Dynamic Thermal Environment in Real Time

A first step toward improving our understanding of the dynamic thermal environment is developing the ability to acquire real-time meteorological data on an individual or small group basis cost-effectively. To achieve this objective, an environmental health monitor---sensor suite must be developed that has the required sensitivity for input to computational models, yet is small enough to be worn by the individual soldier without interference with military mission objectives.

The subject SBIR program addresses this Army objective: Develop a temperature sensor suite for an environmental health monitor that can measure ambient air temperature, relative humidity, wind speed, and radiant energy, and which is configured to be approximately the size of a cigarette pack, is battery operated, and has an RS232 downloading capability.

2. METHODS AND PROCEDURES

This section provides a technical discussion of the methodologies Veritay used to (1) identify currently available, candidate sensor technologies and sensor suite components; (2) test sensor systems and subsystems; and (3) develop sensors and sensor modules. Section 3 briefly adddresses sensor features of key importance to this program. Section 4 provides the results of the tests conducted as well as the rationale behind the sensors/components currently recommended for further development and integration into the sensor suite. Section 5 provides an overview of the current thinking concerning the electronic support system. Section 6 discusses candidate sensor/subsystem modules and describes the evolutionary steps taken to achieve systems integration. Section 7 provides conclusions and recommendations.

2.1 Criteria for Selection and Test

The objective of the sensor selection/test portion of the first-year's effort was to identify and test commercially available, original equipment manufacturer's (OEM) sensors and/or sensor components. The search and testing effort was used as the basis for performing trade-off analyses to determine the optimum combination of sensors and configuration to meet the overall performance, size, weight, and power requirements. Ease of sensor integration, cost, and projected availability were also considered. Although no performance criteria were specified in the contract, the following minimally acceptable performance criteria for each of the measurement parameters of interest were adopted in conjunction with discussions with the technical activity:

- Wind Speed — 0.5 to 4.5 m/s at ±0.5 m/s; 4.5 to 6.5 m/s at ± 10%
- Temperature — 5 to 65°C at ±0.6°C

- Humidity — 0 to 100% RH at ±4.5%
- Solar/Radiant Globe — 5 to 77°C at ±0.6°C
- Solar/Radiant Energy Sensor — No requirement; possibility of locating an off-the-shelf sensor cost-effectively adaptable to this purpose will be investigated.

2.2 Survey of Potential Sensor Technologies and Commercially Available Sensor Elements and Components

Adopting a top-down systems approach to design and development---and having as an ancillary goal the incorporation of off-the-shelf technology whenever appropriate---Veritay subcontracted Akers Associates to (1) perform a comprehensive review of the literature to identify new sensing technologies suitable for integration into the sensor suite, and (2) to perform a comprehensive survey of commercial off-the-shelf sensor elements and/or components.

The search methodology used to identify potential new technologies suitable for integration into the sensor suite included a computer database search using the following key words:

> Anemometer, wind speed
> Relative humidity, humidity, absolute humidity
> Solar detection, radiant detection, thermal detection.

Several technologies were identified, each having distinct advantages and disadvantages; a summary of this literature search is given in Appendix A. One of the primary reasons for conducting this search was to ensure that no new approaches or technologies were overlooked when selecting candidate technologies for integration use in the sensor suite (particularly if commercial, off-the-shelf sensors/elements proved to be unobtainable for any given parameter of interest).

Veritay also asked Akers Associates to conduct a survey of off-the-shelf sensors, sensor components, calibration equipment, and data acquisition systems to identify cost-effective, commercially available items suitable for incorporation into the sensor suite. Environmental parameters searched included sky radiation (solar and radiant), wind speed, relative humidity, and ambient air temperature. In addition to conducting both computerized and manual literature searches (including the Thomas Register, American Chemical Society Laboratory Guide, Sensor Magazine Supplier Guide, etc.), Akers conducted interviews by telephone and/or made personal inspections of vendor products that appeared promising. Akers then prepared a master file cataloging relevant data and equipment literature received. The list of commercially available sensor technologies and sources compiled by Akers is given as Appendix B to this report.

On the basis of this search and subsequent discussions with vendors, Akers Associates concluded that currently available sensor technology can be adapted to meet program objectives.

2.3 Approach to Experimental Test Design

To evaluate the ability of recommended sensor candidates to meet performance criteria under various environmental conditions and to determine potential interference effects (either among sensors/sensor components or between sensors and the body of the unit), Veritay identified two experimental methodologies:

1. <u>Perform initial sensor characterization testing using laboratory bench apparatus capable of generating a variety of environmental characteristics</u>

   Using laboratory bench-type apparatus to perform initial sensor characterization tests (e.g., to determine if precision, accuracy, and operational characteristics of OEM sensors/components were within acceptable ranges) was determined to be a cost-effective and preferable alternative to expensive full-up environmental test chamber testing in certain instances. For example, bench type testing was used to quickly eliminate candidate OEM sensors/components and/or configurations when single parametric measurements were decision factors. This type of testing was also conducted to permit rapid evolutionary development of potential sensor configurations incorporating various combinations of off-the-shelf and customized sensors/components/electronics.

2. <u>Perform certain testing in an environmentally controlled test chamber</u>

   This approach has the advantage of permitting all parameters (e.g., relative humidity, temperature, wind speed) to be maintained under constant control. Since this type of testing is very costly, it was determined that this type of testing should be reserved for evaluating synergistic effects and for conducting validation testing.

It was also determined that solar/radiant evaluations should be performed under outdoor conditions, rather than attempting to duplicate the solar spectrum in an artificial environment. Year two validation testing of the integrated system will be performed using both the outdoor environment and the environmental test chamber located at Research Triangle Park.

2.4 Equipment Used to Test Sensors and Sensor Components

To achieve cost-effective sensor selection, fabrication, and breadboard and brassboard testing (prior to validation testing to be performed at Research Triangle Park during the second year of the program), Veritay configured the test equipment and developed the procedures described in the following subsections.

2.4.1 Bench-top Environmental Chamber

A bench-top environmental chamber was developed to provide a quick assessment of thermistor temperature sensors and candidate humidity sensors. Details of the bench top chamber design are shown in Figure 1. As illustrated, the test environment is contained within a 12-inch-diameter, 11-½-inch high, nalgene "bell jar" seated over a plastic lid seal. Thru-ports on the lid facilitate installing the sensor instrumentation and chamber plumbing lines. Humidity generation and air flow control is provided by a two-speed, cool-mist, ultrasonic humidifier. Chamber temperature above ambient is controlled by a 1500-Watt heater coil, which is inserted into a 1-1/2-inch PVC tube in line with the fan and humidifier air flow. Both humidity and temperature are adjustable, thereby permitting a wide range of relative humidity values to be generated. Corrugated polyethylene hose is used to connect chamber ducts to humidity generator and PVC heater core. Hose disconnects were fabricated from schedule 40 PVC to accommodate various hook-up arrangements between the humidity chamber and generator.

The chamber humidity was varied from 15% RH to 90% RH at ambient temperatures during preliminary testing. Temperatures above 65° C were achievable at the maximum heater power. Insulative material was wrapped around the outside of the nalgene jar, the connecting polyethylene hoses and the PVC plumbing lines to prevent moisture condensation on the walls of the air line tubing when tests were run at high humidity and temperature values.

2.4.2 Calibration Wind Tunnel

Figure 2 presents a schematic drawing of the calibration wind tunnel, which was used to make preliminary evaluations and calibrations of candidate sensors, and to determine their suitability for integration into the sensor suite. The calibration wind tunnel is a closed-circuit tunnel with stable, controlled air flow through a transparent,

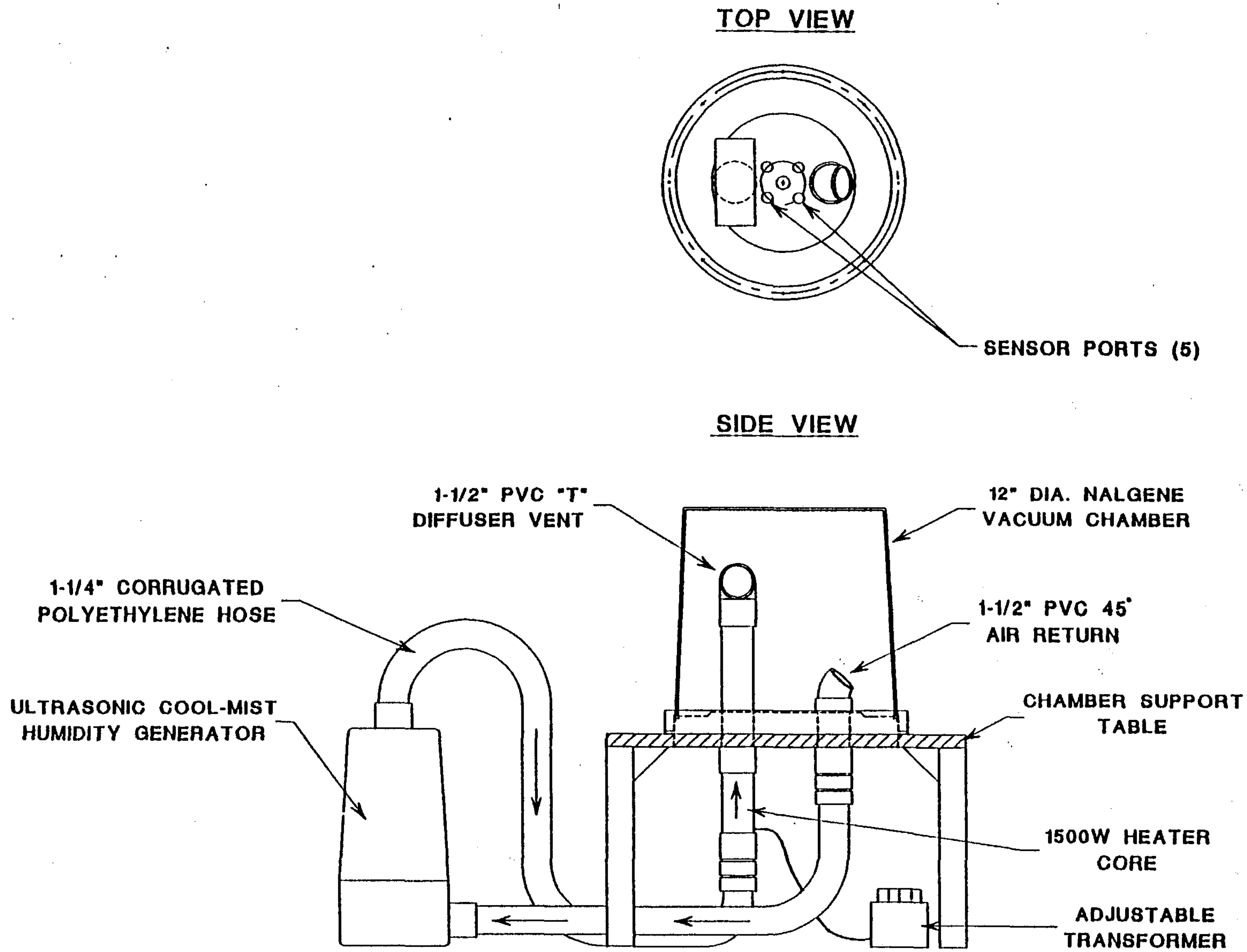

Figure 1. Laboratory Bench Chamber

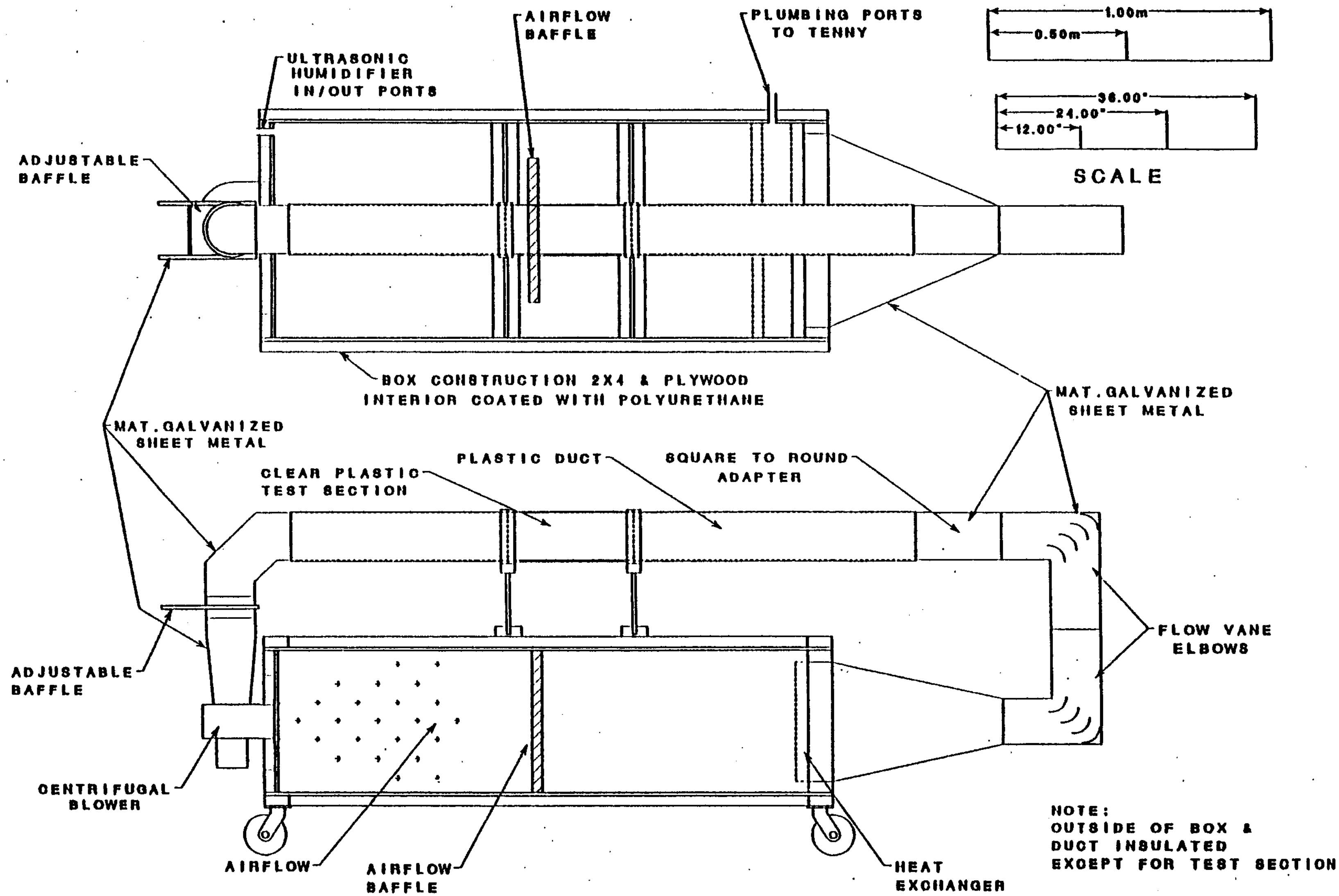

Figure 2. Environmental Test Chamber

7-inch-inside-diameter by 18-inch-long test section. The tunnel is of sufficient size and is suitable for calibrating both individual or groups of wind- speed sensors against standard instruments. It was utilized to assess the influence of wind, temperature and humidity on the performance of groups of sensors. The wind speed capability of the tunnel covers the range from about 0.5 to 6.5 meters/sec.

The wind in the tunnel is generated by a centrifugal blower, which is driven by a shaded-pole, two-speed electric motor operating on 115 volts AC. An adjustable baffle plate is incorporated for restricting the volume flow of air to achieve selected values of wind speed. A variac controller is used for making minor adjustments of the blower motor speed, and, thereby, the wind speed.

The tunnel features temperature control of the air flow over the range of about +5° C to +65° C, within approximately ±0.5° C. Tunnel air temperature is increased by passing it through a hot-water-driven, radiator-type heat exchanger located at the outlet of the air-mixing plenum. Two temperature controlled heating units (not shown in Figure 2) external to the tunnel are used to condition the water temperature. These, together with insulated flexible hoses and a pump, circulate approximately three (3) liters of water through the radiator, and allow the tunnel structure and air inside the tunnel to come to temperature equilibrium---typically in less than an hour. One of the water heaters used is a 1000-Watt Laude® immersion heater emplaced in an insulated water plenum. The second (hooked in series), is a 500-Watt heating unit contained in a Veritay-owned Tenny Junior®, high/low temperature environmental test chamber, together with a second fin-type, water-flow-through heat exchanger unit located inside this test chamber.

The tunnel air flow is cooled using the second of the preceding heat exchangers and elements of the water-based system. This is accomplished by bypassing the immersion heater, directly using the previously noted heat exchanger in the environmental chamber, and employing the refrigeration capability of this same environmental chamber.

The environmental chamber itself has a self-contained Tenny Hermitcool® Refrigeration system, which is a cascade system incorporating two compressors with accurately calibrated capillary tubes in lieu of mechanical expansion valves, and using the non-flammable refrigerants Freon R12 and R503. The operating temperature range of the environmental chamber extends from -80° C to +177° C, and temperature control capabilities within the chamber are claimed to be ±0.3° C over the range of -65° C to +177° C.

The time response, stability and control aspects of attaining and maintaining heating, cooling, or ambient air temperatures within the calibration wind tunnel are aided by extensive use of insulation throughout the tunnel. Closed cell foam insulation panels were installed inside and outside the air mixing plenum, and flexible cellular foam insulation contained within an aluminum foil wrap was applied to the outside of all galvanized and plastic air duct components--except the clear test section of the tunnel, which was encased with a three-inch thick fiberglass insulation removable jacket.

Provisions were made to vary the humidity of the air flowing in the tunnel, to the extent that the humidity of the air can be increased slowly over selected ranges, while holding the air temperature nearly constant. Although this approach does not strictly provide direct humidity control, it permits performance comparison of sensors with standard sensor units as the humidity levels of interest are reached. From an experimental standpoint, the use of this technique enables much more humidity-temperature data to be acquired in a timely manner than would otherwise be possible in a test unit of the size of this calibration wind tunnel.

A commercially available ultrasonic humidifier unit provides an unheated effluent of fine spray droplets into turbulent air flow within the mixing plenum and is used for low temperature humidity tests. At higher temperatures, a dual-element electric hot plate is used to assist the evaporation of water in two conventional 10-1/2" x 14" steel pans within the mixing plenum. Relative humidity is adjusted by varying the temperature of the water.

2.4.3 Pulsed Duty Cycle Circuitry---Wind Speed

Circuitry was developed at Veritay to drive the Testoterm model 1049 "hot bead" anemometer using a pulsed duty cycle. The circuit consisted of a voltage comparator and switching logic to appropriately control two current sources that were used for heating and monitoring the cooling rate of the thermistor bead.

2.4.4 Indoor Radiant Energy Test Fixture

A test fixture consisting of a point light source and sensor mounting hardware was devised to assess the angular response of candidate radiant sensors. In particular, a 600-Watt, quartz projector bulb served as the point light source and was separated from the sensor under test by approximately 47 inches. The fixture permitted pivoting of the sensor ±90° in alignment with the quartz light source.

2.4.5 Reference Instrumentation

Test apparatus and supporting test equipment used for the purposes of evaluating sensors was monitored using instruments conforming to either ISO standards or NIST traceable standards. The Testoterm model 452 and its associated environmental test probes was the sole reference for tracking temperature, relative humidity and wind speed measurements in all of the test evaluations performed. Table 1 contains a complete list of test equipment and the experiments in which they were employed.

EQUIPMENT	DESCRIPTION	APPLICATION
Testoterm 452 Using Test Probes:	Expandable environmental measuring instrument	Probe Interface Instrumentation
9540	Mini-Vane Anemometer	Initial reference for tunnel wind speed testing
1049	Telescoping "Hot Bead" Anemometer	"Hot Bead" pulsed-power and energy analysis
9760	Dual Function Probe: RH and Temperature	Reference for bench and tunnel fixtures used in RH and temperature measurement
1045	Three Function Probe: RH, Temperature and "Hot Bead" Anemometer	Tunnel wind speed reference
1549	Non-telescoping Hot Bead Anemometer	Integrated Black Globe, "Hot Bead" interference tests
Fluke 87	3 ½ Digit Multimeter	Power Supply Voltage Measurement Radiant sensor testing (outdoor)
Fluke 8050A	4 ½ Digit Multimeter	Calibration of signal conditioning circuitry Radiant sensor testing (indoor)
H.P. 34401A	6 ½ Digital Multimeter	Anemometer Thermistor measurement and PC DAS circuit calibration
LeCroy 6810	Waveform Digitizer	Anemometer energy consumption evaluation
B&K 1660	Triple Output Power Supply	Powered circuitry for for "Hot Bead" Pulse-Power analysis

TABLE 1. Test Instrumentation and Equipment

2.4.6 PC Data Acquisition System (DAS)

Monitoring of the wind tunnel environment was accomplished using the Testoterm instrument via an RS-232 interface in conjunction with an IBM compatible AT personal computer (PC) system. The PC system was also used to monitor the sensor devices under test using the MetraByte DASCON-1 multifunction analog and digital I/O expansion board interface. The DASCON-1 is primarily used for analog data acquisition purposes. The features of the DASCON-1 include 12-bit resolution, ± 2.0475 full-scale input (0.0005 resolution), 4-channel multiplexer and a digitizing rate of 30 channels per second.

Computer control of both the wind tunnel and sensor acquisition systems was implemented using program code existing at Veritay. The software, written in Microsoft® QuickBASIC, facilitated program changes for adaptation to various test procedures. It also provided a means of converting, scaling, timestamping and formatting data for subsequent spreadsheet data analysis.

2.5 Procedures

2.5.1 Humidity

The bench humidity chamber was used for the assessment of three candidate relative humidity sensors:

- Panametrics
- Thunder Scientific
- Hy-Cal

Each of the three candidate humidity sensors were mounted in a clear plastic sleeve to facilitate installation into the bench test chamber. The Testoterm dual probe, model 9760 acted as the reference for temperature and humidity and was inserted along with the three sleeves from the bottom side of the chamber. All four sensors were positioned upright and were located within a three-inch diameter circle. The exposed end of each sensor was approximately three (3) inches above the bottom of the chamber surface.

Tests were conducted at selected values over the humidity and temperature ranges varying from 13% to 98% RH and 25° C to 55° C. Humidity in the chamber environment was maintained using the ultrasonic modulation adjustment on the cool mist humidifier. Temperature was also controlled using a variac transformer to adjust the power to the heater coil.

Problems with achieving high humidity at high temperatures were overcome by covering the nalgene jar with one-inch foam insulation. This helped prevent condensation from forming on the chamber walls. Wet towels draped inside the chamber in front of the airflow outlet also served to increase the humidity.

Tests were also performed to examine the interchangeability and relative precision between three Hy-Cal IH-3602-A sensors using the calibrated wind tunnel. The Testoterm "mini-vane" anemometer, model number 9540, was used as the wind speed reference. The Testoterm dual probe, model 9760, served as the reference for temperature and relative humidity. The Testoterm reference probes were inserted through the wall of the tunnel test section to a depth of two (2) inches and were situated radially at the midpoint of the test section. The three Hy-Cal sensors were aligned as shown in Figure 3 and located approximately four (4) inches downstream from the reference probes in the center of the test section.

The signals from each Hy-Cal sensor were signal conditioned with amplifiers situated on a patch panel located outside the test section. The PC DAS system was used to simultaneously record the three (3) Hy-Cal sensors and Testoterm reference data at one-second intervals. Tests were conducted at nominal wind speeds of 2, 3, 4.7, 6.3 and 7.1 m/s. Each wind speed level was maintained for a minimum for four (4) minutes to permit sensor equilibration.

2.5.2 Wind Speed

The objective of this test was to compare the level of energy required to operate a conventional "hot bead" anemometer in a continuous mode as opposed to a pulsed duty-cycle mode. The Testoterm model 1049 probe was used for this purpose. Both tests were performed in the wind tunnel at ambient temperature at wind speeds ranging from 0 to 7m/s.

The experimental procedure for obtaining the level of energy consumed for the conventional "hot bead" anemometer concept required determining the current through the model 1049 probe while monitoring the voltage across it. Current measurement was achieved by measuring the voltage across a one-ohm shunt resistor inserted in series with the probe's 200-ohm thermistor bead terminals. The device was connected to the Testoterm 452 and operated normally while monitoring both the shunt resistor and "hot bead" thermistor voltages with the LeCroy waveform digitizer. The product of the two measurements, was then integrated to obtain the energy dissipated by the thermistor bead.

Assessment of energy consumed by the duty cycle concept was accomplished in a similar manner. Special switching circuitry, used in place of the Testoterm 452 instrument drive electronics, was adapted to the Testoterm model 1049 probe to provide duty-cycle operation. The circuit incorporated two constant current sources, control logic and a voltage comparator. A single cycle consisted of first heating the 1049 thermistor bead using a 100-mA current source. Once the temperature of the bead reached a nominal 100° C, a voltage level detector switched the current source to 1mA, allowing the bead to cool. During this period the LeCroy waveform digitizer was

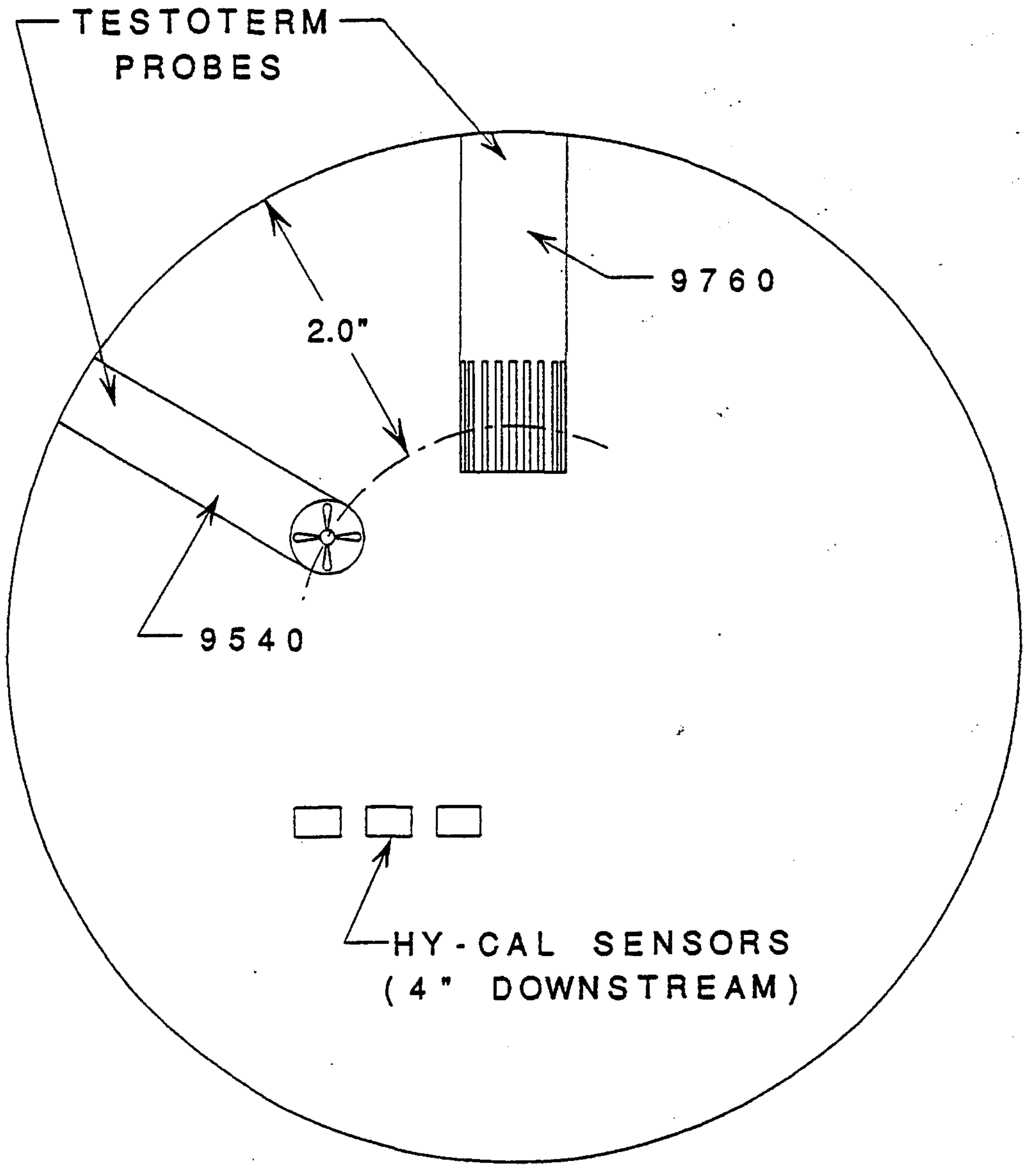

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Figure 3. **Orientation of Reference Probes and HY-CAL Sensors in Test Section**

used to record the voltage across the thermistor bead, obtaining both the input power interval and the response of the thermistor as it cooled.

To evaluate the duty cycle concept as a candidate scheme for wind-speed measurement, the cooling rate of the thermistor bead was recorded in a series of tests which were performed at wind speeds of 0,1.6, 4.7,and 7.6m/s.

2.5.3 Radiant Energy

Indoor testing of solar (visible spectrum) sensors was performed using the 600-Watt, quartz-filament test fixture. Measurements were taken for each of two sensors at 15-degree intervals over the range from -90 to +90 degrees. The first sensor tested was a thin-film thermopile type manufactured by ARMTEC. Its output was measured directly using the Fluke 8050A digital voltmeter. The second sensor, manufactured by Hamamatsu, was a highly sensitive silicon-photo-diode device. It was evaluated in the photoconductive mode using a current-to-voltage amplifier scheme for signal conditioning purposes. This output was subsequently measured with the Fluke 8050A digital voltmeter.

Preliminary outdoor testing was also performed to compare the ARMTEC solar and IR sensors in sunny/light haze and overcast weather conditions. This was done near solar noon, and consisted of measuring the thermopile output at angles of -90, -45, 0, +45, +90 degrees away from the sun. Results are given in Table 2 (Section 4.4).

3. SENSOR DEVELOPMENT

3.1 Candidate Sensing Technologies

Various sensors were selected for laboratory evaluation to determine the appropriate sensing technology to be employed for measuring the environmental parameters of wind speed, relative humidity, solar and infrared radiation. Thermistor technology was used for the measurement of ambient temperature.

3.2 Wind Speed

The primary criteria for a miniaturized wind speed sensor is that it must be capable of measuring wind speed omnidirectionally. This can be done with either a mini rotating cup or a heated surface. The rotating cup is a mechanical system that typically exhibits high maintenance and low reliability. The rotating cup system consists of a vane system that rotates around an axis and incorporates a mechanical system that counts the speed of rotation. The latter is translated into wind speed. The system is not effective at very low wind speeds because of inherent frictional forces.

The conventional "hot bead" anemometer is another technique for measuring wind speed; this technique offers better sensitivity than the rotating cup. Its operation is based on monitoring the electrical power required to heat and maintain a thermistor bead at a nominal temperature. Wind speed can be related to the rate of heat transfer from the bead surface to the environment in terms of the quantity electrical power delivered. This method, however, requires support electronics and a considerably larger energy supply as compared to the rotating cup anemometer.

An alternative methodology using less energy is based on the cooling rate of a pulsed heated probe. In this technique, the probe is heated to a given temperature above ambient and then allowed to cool. The rate of cooling is a function of the wind speed around the pulsed probe bead.

Preliminary experiments indicate that the use of this pulsed, hot-bead technique for the measurement of wind speed is viable for use in the sensor suite. A combination of using a short, well defined energy pulse to heat the probe to some predetermined level above ambient temperature, followed by monitoring its cooling rate should give a reliable wind speed indication with the desired sensitivity and range while conserving energy.

3.3 Relative Humidity

The presently favored candidate technology for a miniaturized relative humidity sensor is based on thin-film capacitance. This technique measures the capacitance across a hydrophilic thin film. The electrical properties of the thin film are a function of the film's water or moisture content. These units have been used successfully as Original Equipment Manufacturer (OEM) components in many off-the-shelf items. They are readily available and inexpensive in large numbers.

Three different thin-film capacitor relative humidity devices were evaluated: Thunder Scientific, Panametrics, and Hy-Cal. The test results indicate that the Hy-Cal units are preferred. They contain built-in circuitry that allows one to supply 5VDC power and obtain a direct readout of RH (as indicated from an output that ranges from 0 to 100 mV). Sensors from different lots were tested and observed to be within 3% of each other when compared to the standard Testoterm calibrated sensor.

3.4 Solar Radiation

Candidate existing technology for solar radiation measurement includes either a photoelectric cell or a thermopile. A particular problem that exists with both the photoelectric and thermopile devices concerns the observed reading being a function of the incidence angle of the radiation impinging on the sensor. This occurs because the energy flux in an incoming beam of radiation spreads over a larger surface area of the detector when the beam is incident at an angle away from the perpendicular to the detector surface. The energy incident on the detector varies as the cosine of the incidence angle of radiation---a feature referred to as Lambert's Cosine Law. To minimize the error in measuring the radiation environment arising from such angular effects of incident radiation, approximately six (6) photoelectric cells or thermopile sensors are required.

Hamamatsu has a very small photoelectric cell, and ARMTEC has a thermopile-based sensor with fuzed silica as a visual band pass filter. The advantage of the thermopile-based system is that the sensors can be placed in series to allow for analog integration of their energy level.

Alternatives to using many sensors oriented in different directions to overcome the problems of obtaining accurate measurements of radiation incident from essentially all directions is to use either (1) sensors constructed in the form of curved segments to receive radiation from annular sectors, or (2) a sensor such as a spherically symmetric black globe to integrate radiation from all angles.

4. SENSOR EVALUATION

Based on the technical review and analysis of OEM sensor elements, potential candidates were evaluated to select which sensors should be included in the integrated Environmental Health Monitor---Sensor Suite.

The performance of individual sensors were evaluated, and the interference effects of selected combined sensor elements were explored to assess the potential for using sensors in close proximity in a miniaturized integrated sensor suite.

4.1 Temperature

Temperature OEM sensors were not evaluated under this contract because of the simplicity of the measurement via the use of a thermopile or a thermistor. The thermistor was identified as the ambient air temperature sensor of choice because of its power and signal conditioning requirements, its reliability, and its ready availability. Several OEM manufacturers stock products capable of meeting the temperature range of interest (i.e., 0° C to 64° C with accuracies better than 0.5° C).

4.2 Relative Humidity

The output response was obtained for three candidate sensors as a function of relative humidity. The relative humidity was varied at three different temperature values (35° C, 45° C, and 55° C). Figure 4A provides a plot of the data taken using the Hy-Cal humidity sensor (Model IH-3602-A); these data are within a 4.5% experimental error when compared to the reference humidity sensor, demonstrating that the commercially available Hy-Cal is suitable for incorporation into the sensor suite.

Figure 4B illustrates the data obtained from a Panametrics MC-2 humidity sensor. Although the response curve may not be linear, the spread of the data is beyond the acceptable 4.5% variation from the Testoterm reference humidity sensor, thereby removing this sensor from contention. Figure 4C shows the data taken from the Thunder Scientific PC-21-1C (02); the response curves illustrate that this sensor is not temperature compensated. Additional support electronics would be required to counter temperature effects so as to determine relative humidity within acceptable error; thus, this sensor also was rejected as a candidate for inclusion in the temperature sensor suite.

To determine if off-the-shelf Hy-Cal sensors from different lots could be reliably used as replacement sensors without the need for additional calibration, Veritay obtained Hy-Cal sensors from three different lots and tested them under different wind speed and relative humidity sensors. Figure 5 depicts data taken at low (<20%), medium (40-50%) and high (80-90%) relative humidities as a function of wind speed. The test result show excellent consistency among sensors to within less than 3%RH units.

Clearly, the Hy-Cal sensor is the most consistent of the three selected for testing following an intensive search of possible candidate sensors; furthermore, the variation between lots is within acceptable parameters and the cost per sensor is also within targeted ranges.

4.3 Wind Speed

While the standard, hot-bead anemometer permits omni-directional wind speed to be determined, the power consumption necessary to constantly maintain the temperature of the hot bead 100° C above ambient air temperature is not consistent with program objectives (particularly the goal of reducing power demands). The primary power drain in the system can be traced to the wind speed measurement sensor.

To reduce anemometer power requirements, an innovative technique has been devised. The anemometer is pulsed with a given amount of energy to raise the hot bead temperature to a given value above ambient. When the temperature reaches this pre-set value, the power is turned off, and the decay curve of the hot bead being cooled by the wind is observed. Figure 6 illustrates the cooling curve over a range of wind speeds. When the first derivative of the rate of change in temperature as a function of time for each of the different wind speeds is calculated, there is considerable differentiation among the various wind speeds. As shown in Figure 7, the resolution among wind speeds, as determined from the first derivative of the cooling curve, is more than adequate to determine the wind speed at a resolution of ±0.5 m/s. The supporting algorithms to convert the hot-bead anemometer signals into windspeeds, such as those given in Figure 7, are still being developed.

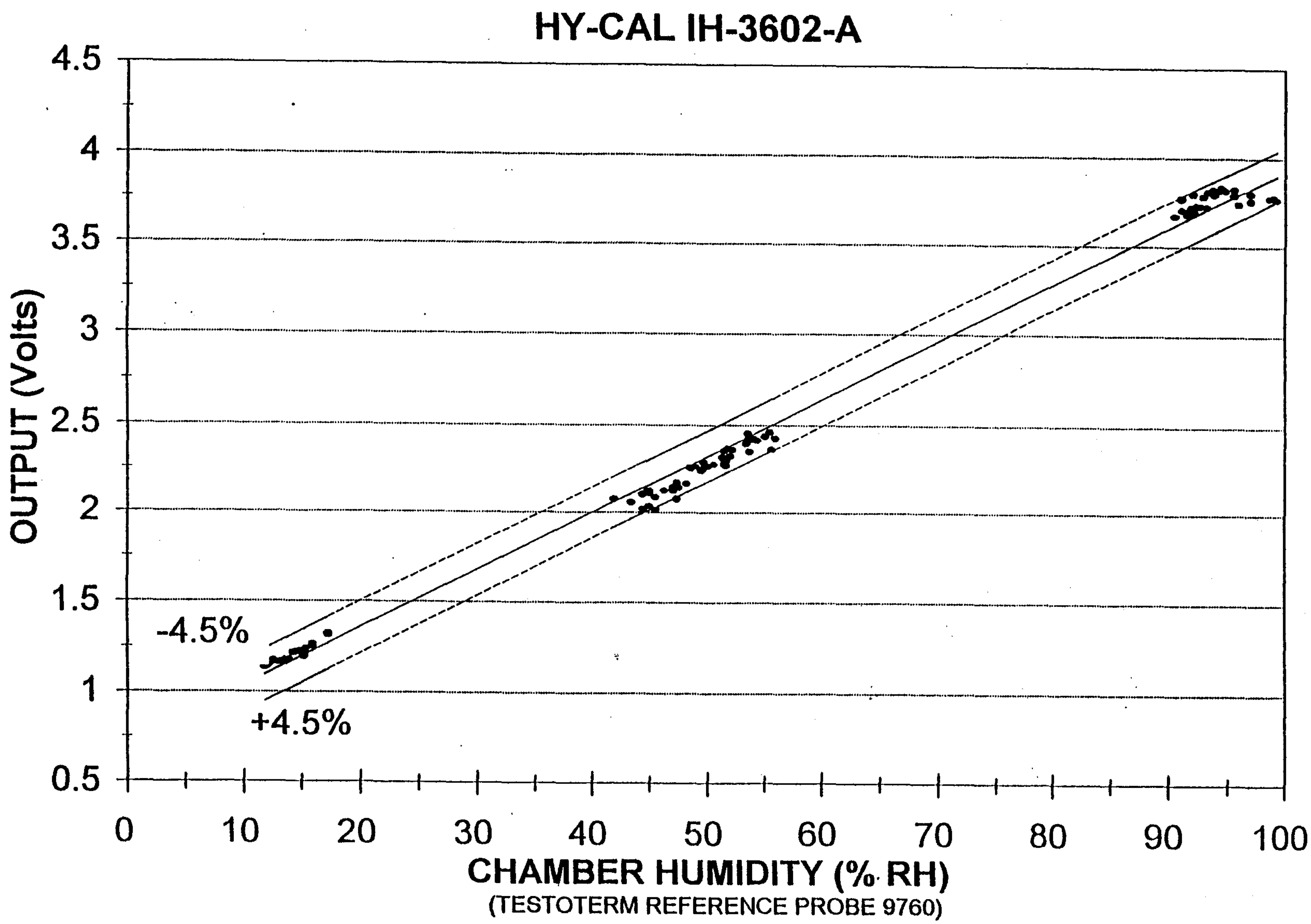


Figure 4A. Output Response for HY-CAL Humidity Sensor

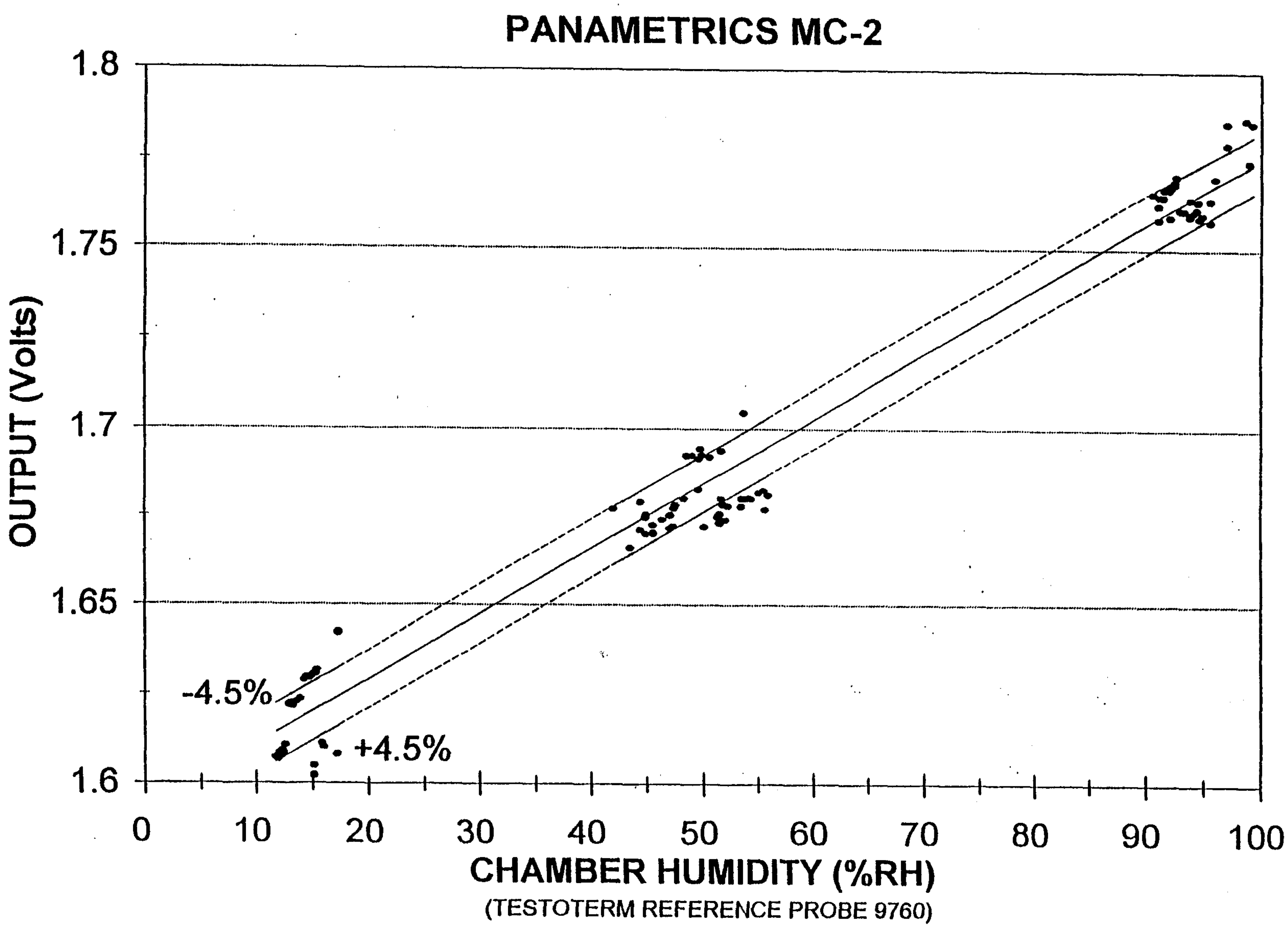


Figure 4B. Output Response for Panametric Humidity Sensor

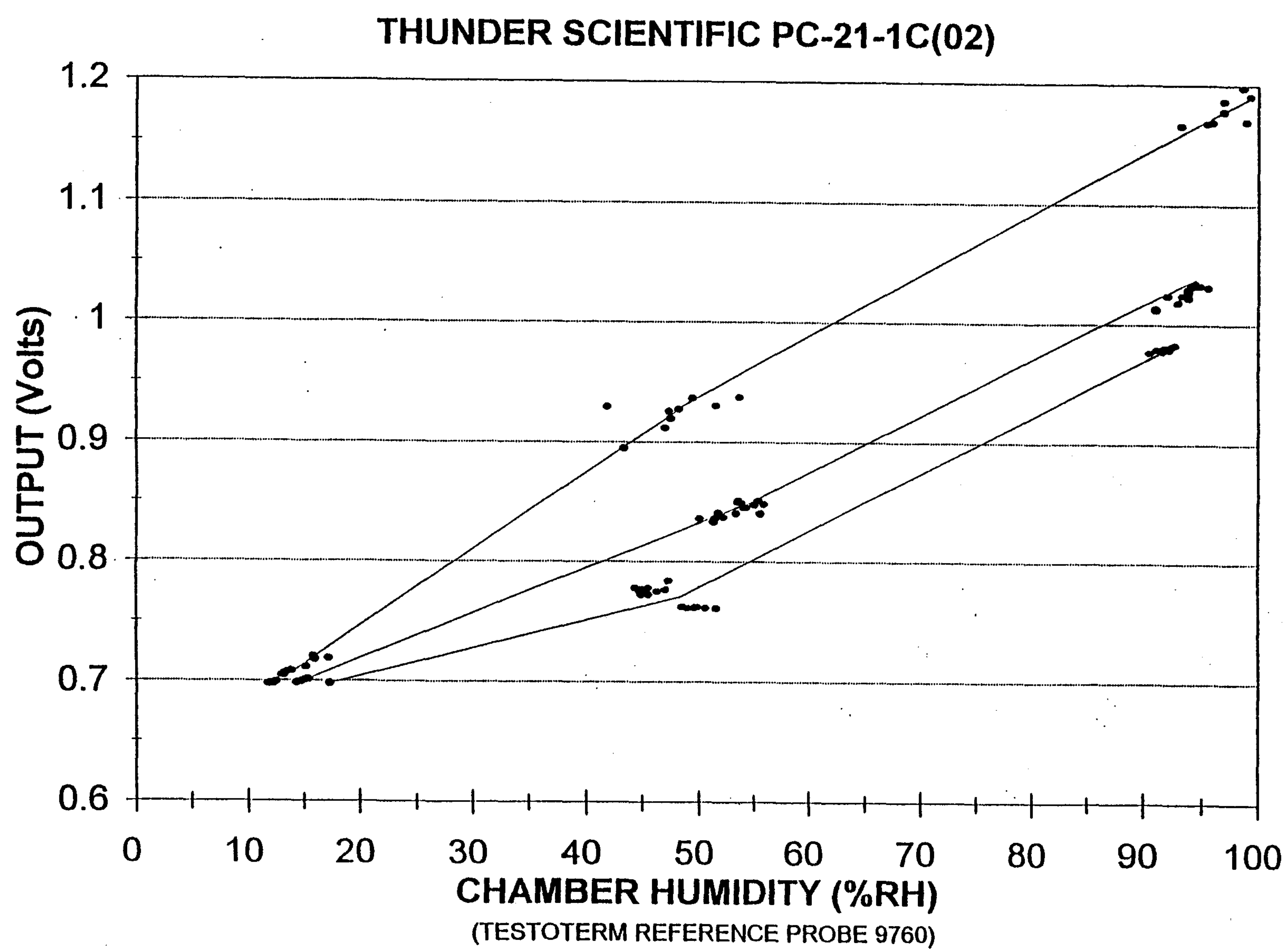


Figure 4C. Output Response for Thunder Scientific Humidity Sensor

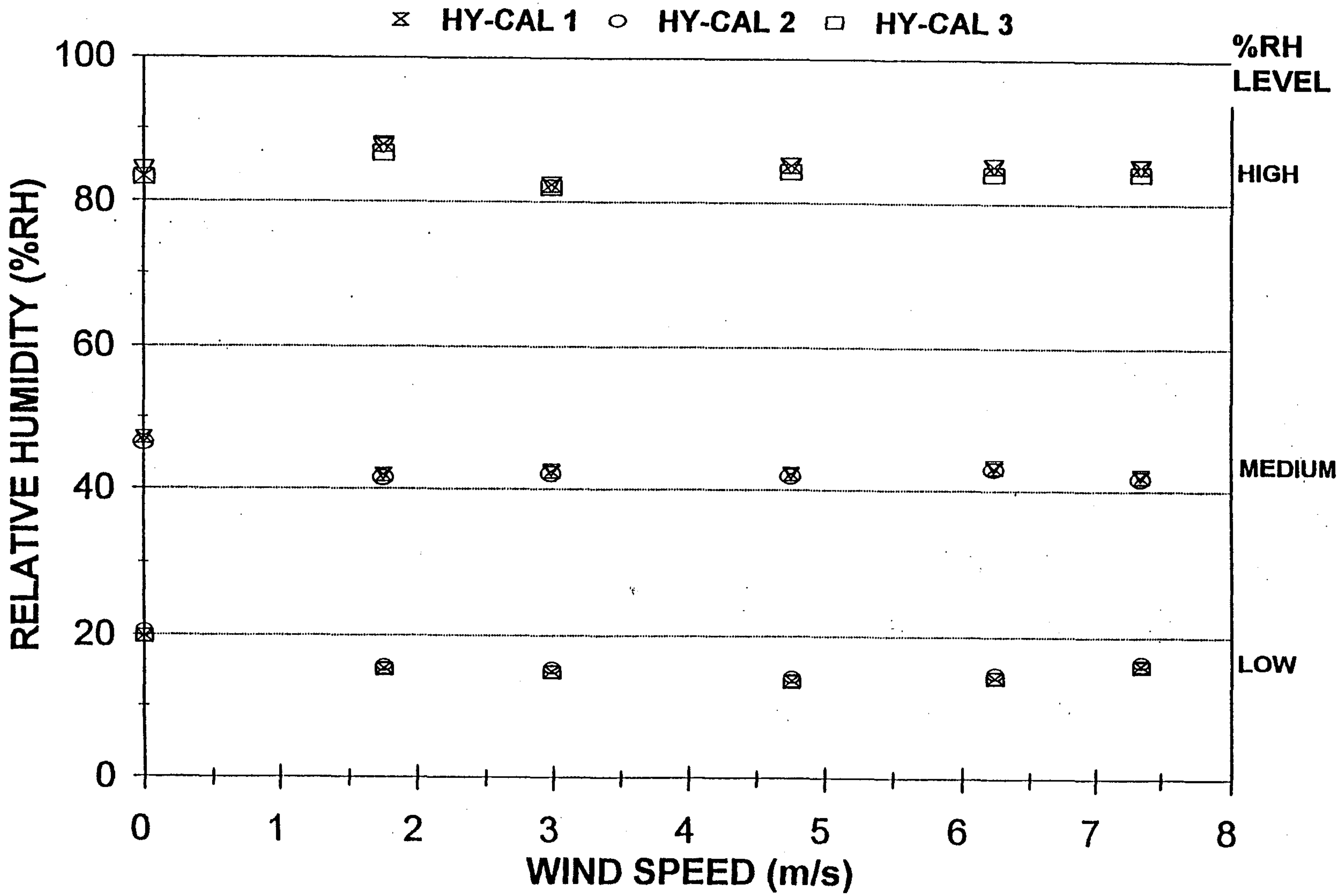


Figure 5. Comparison of HY-CAL IH-3602-A Sensors in Wind Tunnel

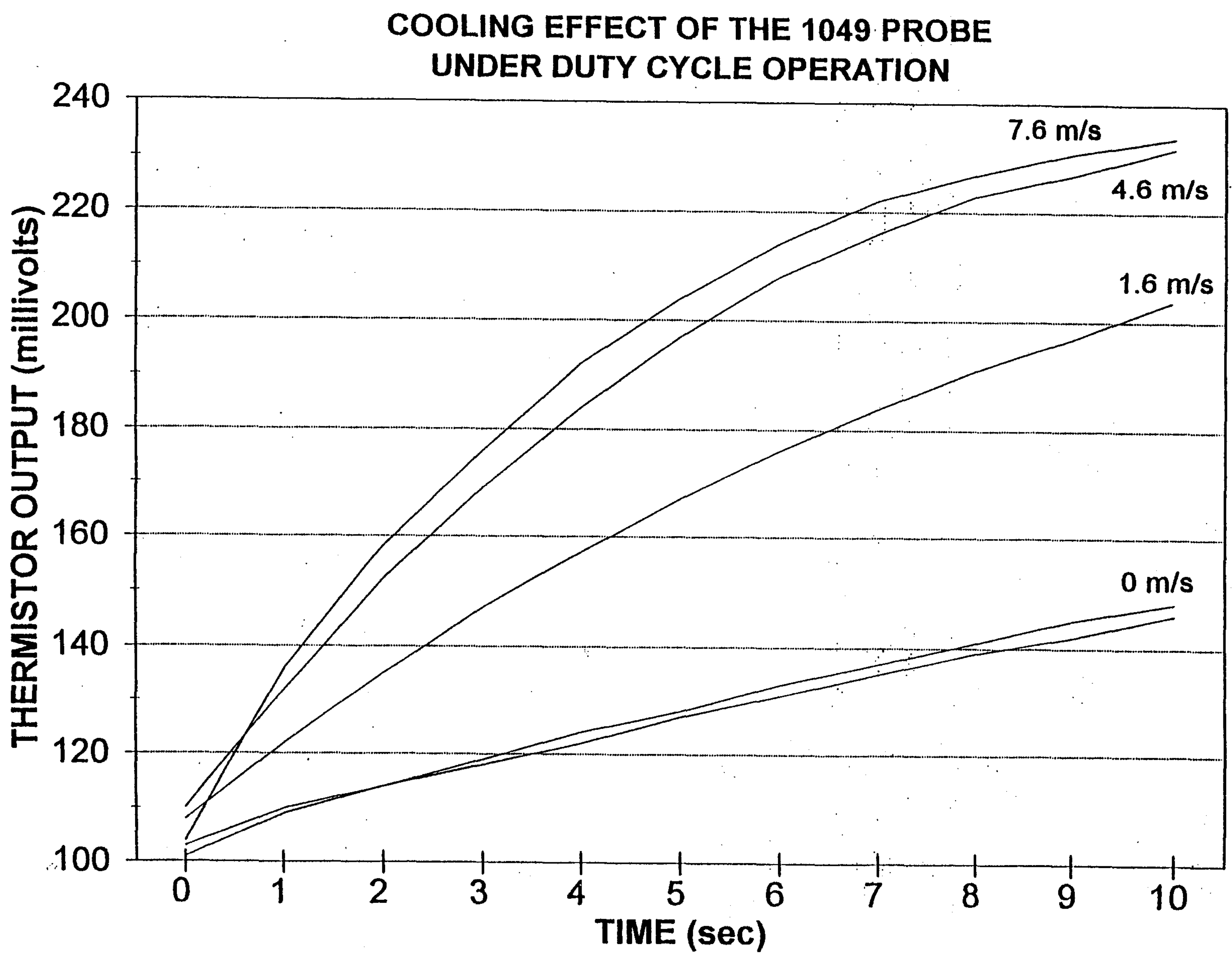


Figure 6. **Cooling Effect of Testoterm Anemometer Probe Under Duty-Cycle Operation**

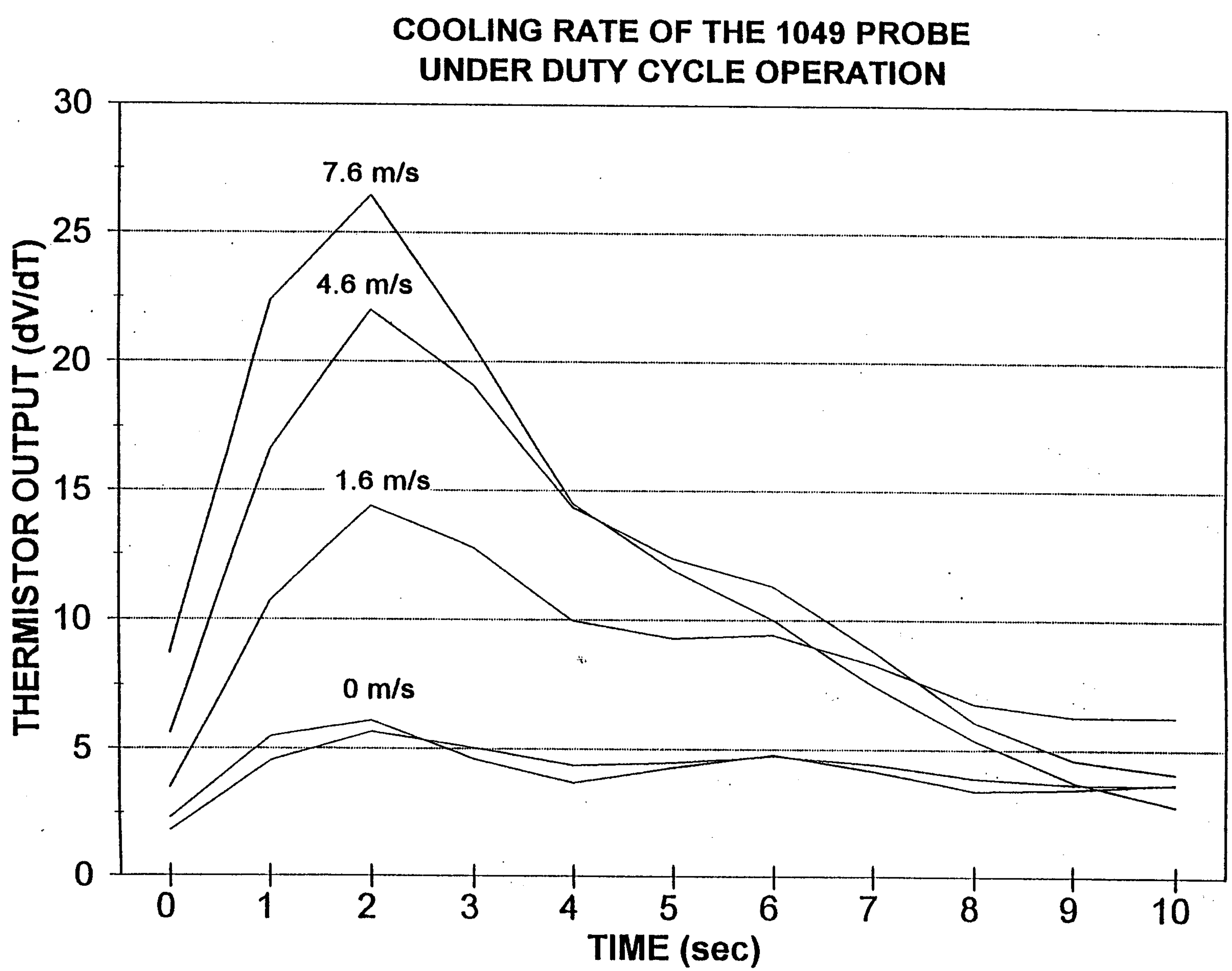


Figure 7. Rate of Cooling for Testoterm Anemometer Probe Under Duty-Cycle Operation

A comparison of the energy consumed by the Testoterm hot-bead anemometer in both continuous and pulsed modes is illustrated in Figure 8. In the continuous mode, the anemometer is constantly heating the hot bead to hold it at a given temperature. The result is a constant energy demand. In the pulsed mode, the anemometer is heated to the same set point, and then allowed to cool by turning the heating mechanism off. In the cooling phase, a small amount of energy is required to monitor the hot bead temperature. Figure 8 illustrates the energy saved by using the pulsed mode of operation.

A modification of this approach is to heat the hot bead a nominal amount above the ambient air temperature (e.g., 10° C) and observe the time constant for the cooling curve to decay. In this way, power would only have to be used during the initial heating of the hot bead. If the hot-bead anemometer is cycled every 15 seconds, and the sensor is only heated for a few seconds, then over a period of three minutes, twelve wind speeds would be determined and averaged to give the average wind speed and lessen the effects of short-duration wind gusts.

If pulsed every 10 seconds, the anemometer consumes approximately 25% of the energy used by the continuously heated hot bead; if pulsed every 20 seconds, it uses approximately 16% of the energy required by an anemometer in continuous mode.

One way to reduce overall sensor-suite size is to combine individual sensors into one or more physically integrated module(s) capable of assessing more than one parameter of interest (e.g., wind speed and radiant energy). Such a combination must be accomplished however, without introducing unwanted interference effects. Figure 9 shows one such combination sensor module: an integrated black globe/hot-bead anemometer. An experiment was conducted using an integrated sensor of the type shown in Figure 9 to determine the impact of physically integrating a hot-bead anemometer and a 0.875-inch black globe, with special emphasis on observing sensor interference effects. Figure 10 shows the observed wind from the anemometer as a function of the distance of the hot bead from the black globe surface. The hot bead was evaluated flush with the globe surface and at separation distances of 0.125 inch (3.2 mm) and 0.25 inch (8.3 mm) from the globe surface. Preliminary data indicate that the wind speed taken by the hot bead anemometer mounted in this fashion is approximately 8% below the reference wind speed over the range of concern up to 6.5 m/s. Further experimentation is required to determine if the interference effect of the black globe on the anemometer can be corrected using calibration techniques.

4.4 Radiant Energy

Several approaches to measuring mean radiant energy were considered, including radiometers, black globes, thermometers, and novel concepts requiring various degrees of advanced development.

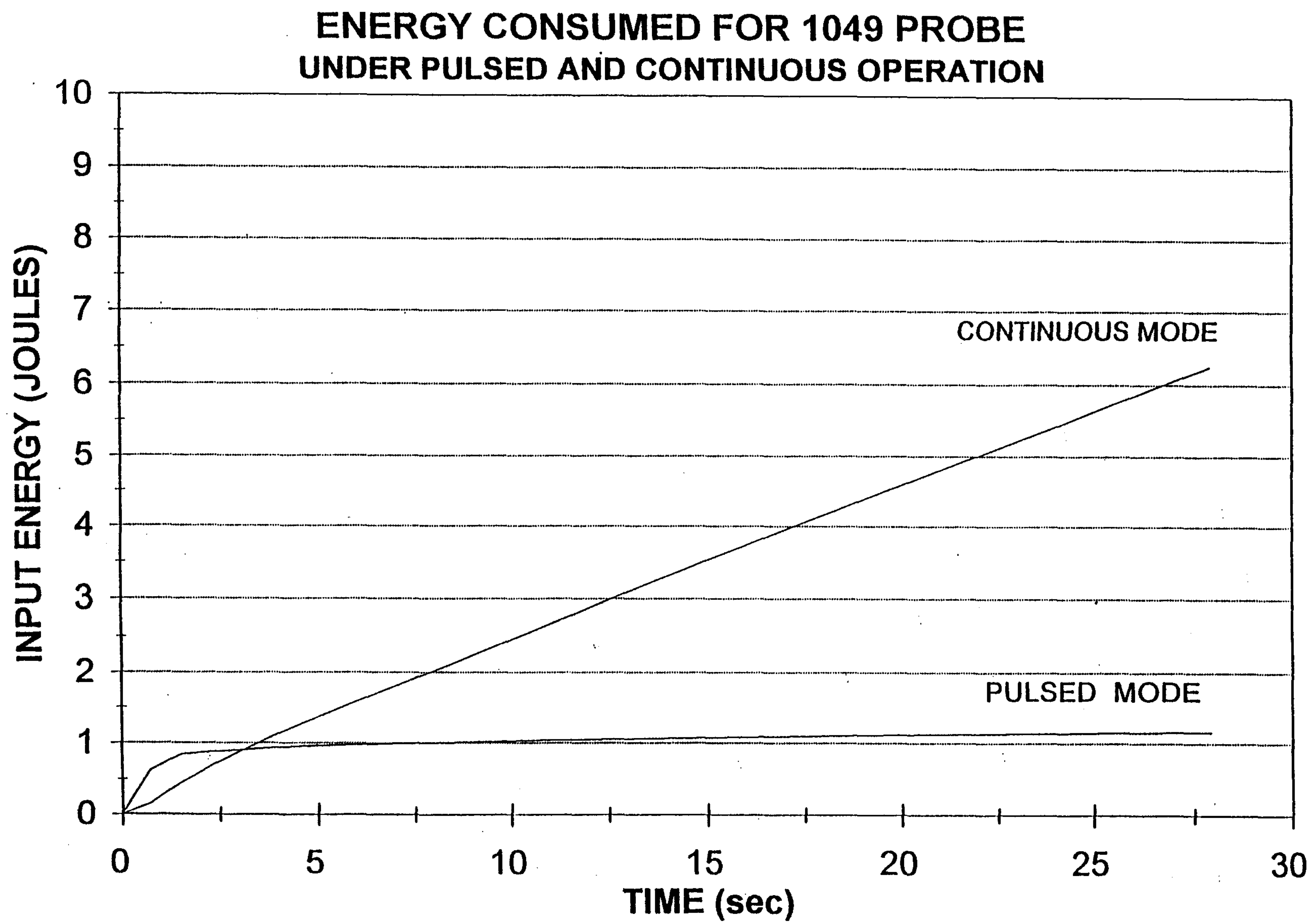


Figure 8. Comparison of Energy Consumed Between Continuous and Duty-Cycled Anemometer Probe

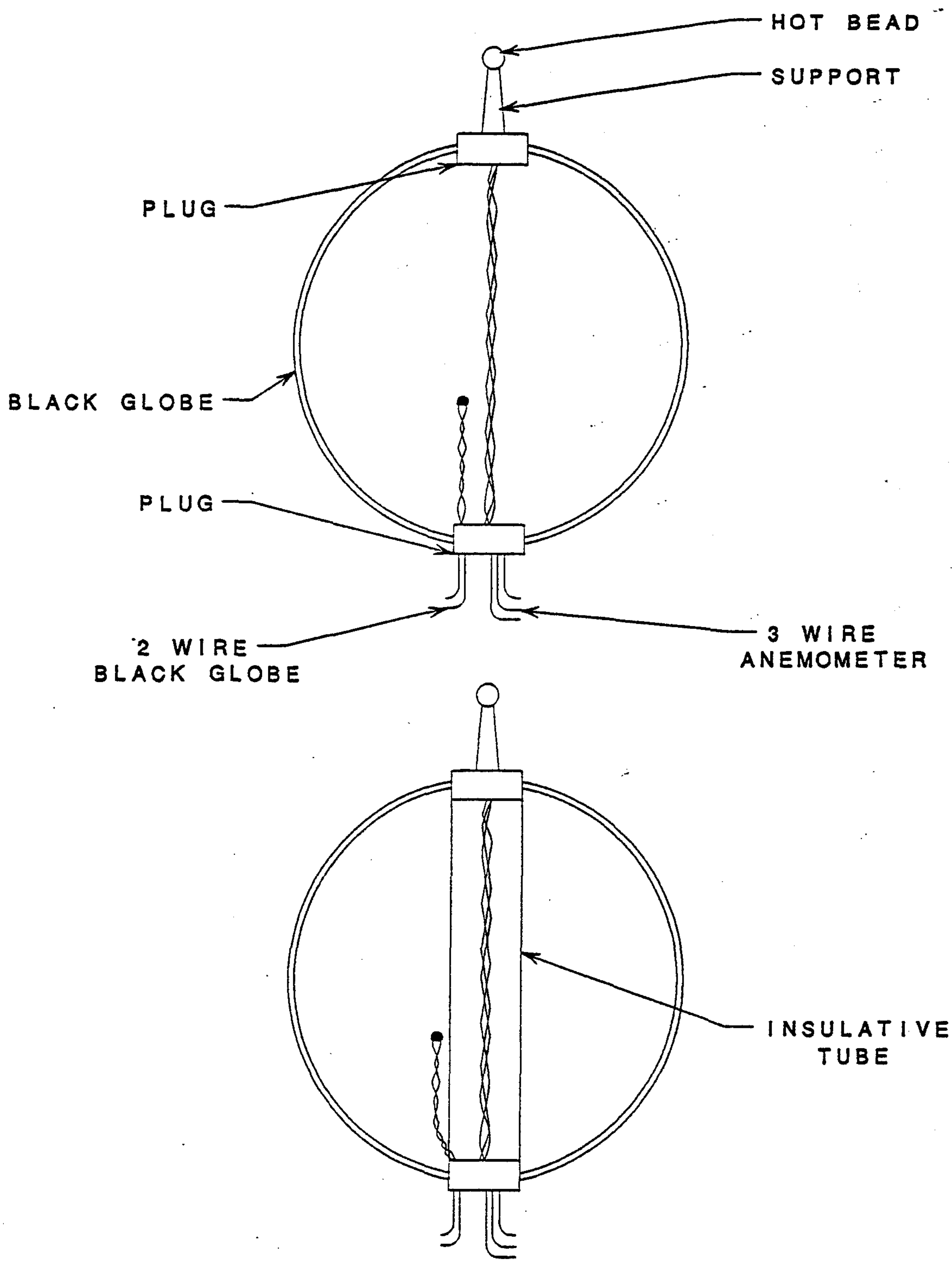


Figure 9. Integrated Black Globe Hot Bead Anemometer

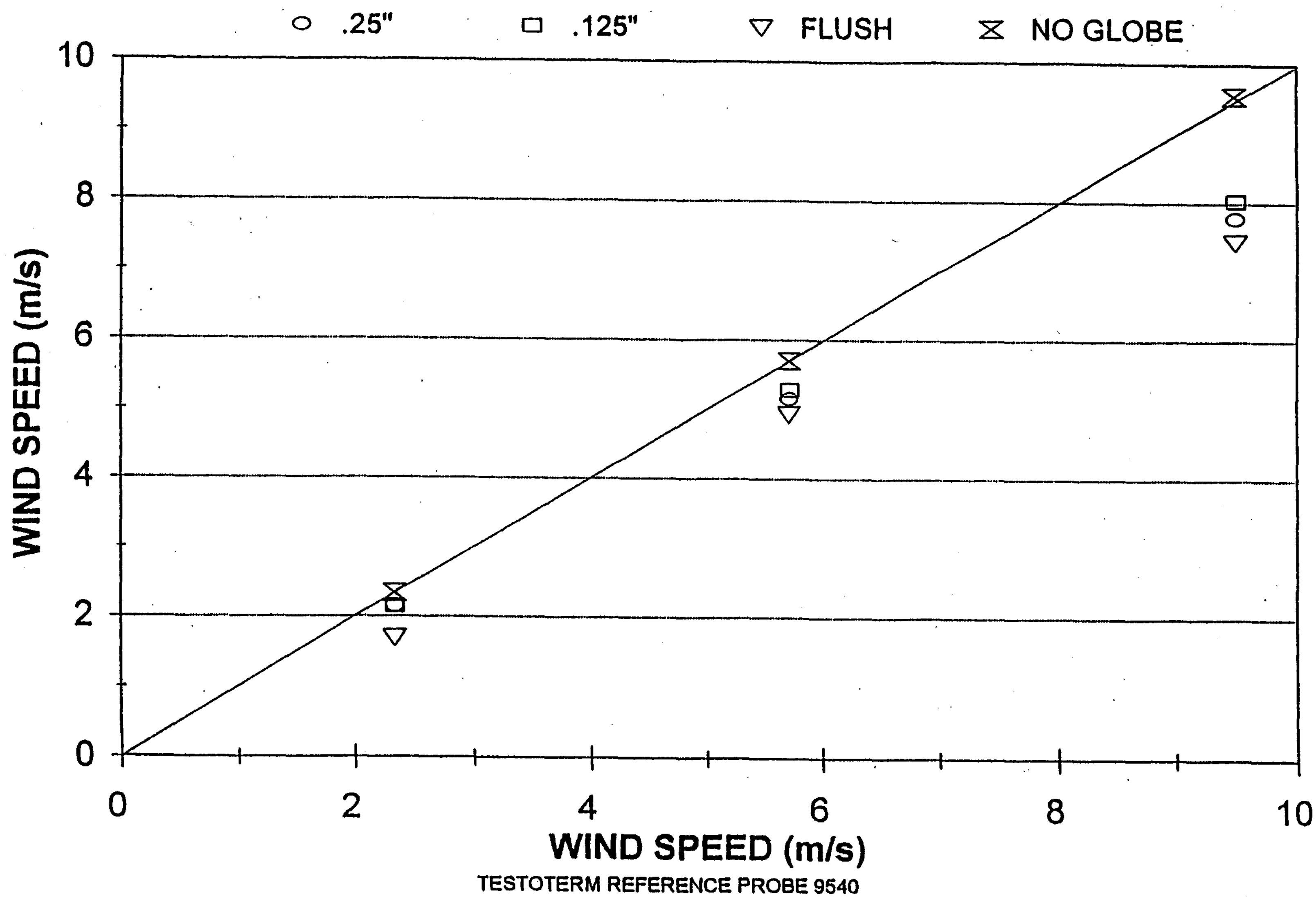


Figure 10. Effect of 7/8" Black Globe Orientation to Hot Bead on Wind Speed Measurement

Radiant energy measurements can be obtained using either the conventional black-globe or the solid-state thermopile sensors marketed by several different manufacturers. Figures 11 and 12 show the indoor radiant test results obtained for the ARMTEC 620-073201 and Hamamatsu S1133-02 solar (visible) sensors, respectively. The cosine response according to Lambert's law is evidenced in both curves; the ARMTEC curve is slightly modified since the thermopile film is set back a small distance from the face of the sensor housing (as compared to the Hamamatsu radiant sensor, which has the thermopile film located at the face of the sensor housing). The solid-state themopile sensors can be used for either solar or infrared radiation input, depending upon the filter material placed over the face of the sensing element. To take a solar reading, a glass filter is used; to take an infrared reading, a polymer material is used.

Preliminary outdoor tests were conducted at the Veritay facilities to ascertain the response of the ARMTEC solar (visible) and infrared (8-14 micron) sensors. The data were taken with zero angle normal to the direct sun. Table 2 summarizes the observations; these raw data are in millivolts (not calibrated to Watts/$m^{2})$. Table 2 presents a comparison of the ARMTEC solar (visible) and IR sensor data that were measured in preliminary outdoor tests.

SENSOR	CONDITION	-90 Deg	-45 Deg	0 Deg	+45 Deg	+90 Deg
SOLAR	SUNNY, LIGHT HAZE	9.7	33.4	190.5	52.0	9.6
	OVERCAST (TOTAL)	18.8	21.9	23.8	19.2	19.2
IR	SUNNY, LIGHT HAZE	6.3	6.1	6.2	6.1	6.1
	OVERCAST (TOTAL)	2.0`	2.1	2.3	1.9	1.7

TABLE 2. PRELIMINARY OUTDOOR SOLAR AND IR SENSOR EVALUATION

The preliminary results indicate there is a large variation in the solar (visible) spectrum between a clear and an overcast day. The infrared energy can be seen to be essentially constant over the observed sky angle, but does vary based on cloud conditions.

Investigation revealed that no radiometer sensors, other than the black globe, currently exist that are capable of achieving integration over a sufficiently wide angular field of view. One concept that promised to achieve the requisite angular integration was a global radiation sensor that used a novel coating technology with alternating black and white bands. Preliminary investigation of this concept indicated that development well beyond the scope of this contract would have been required to achieve implementation. Therefore, it did not warrant further consideration under this contract.

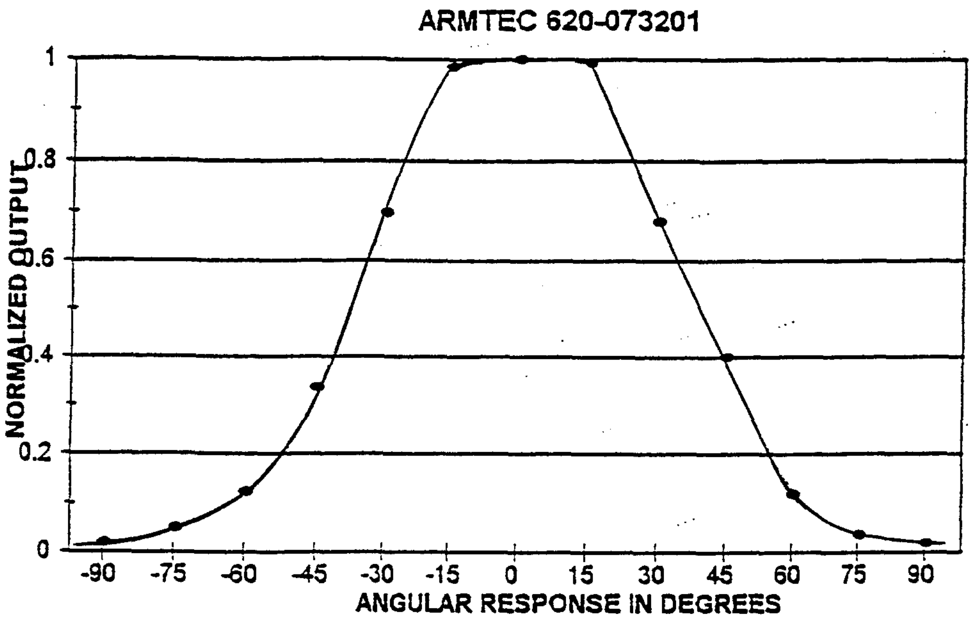


Figure 11. Normalized Angular Response of Armtec 620-073201 Solar Sensor

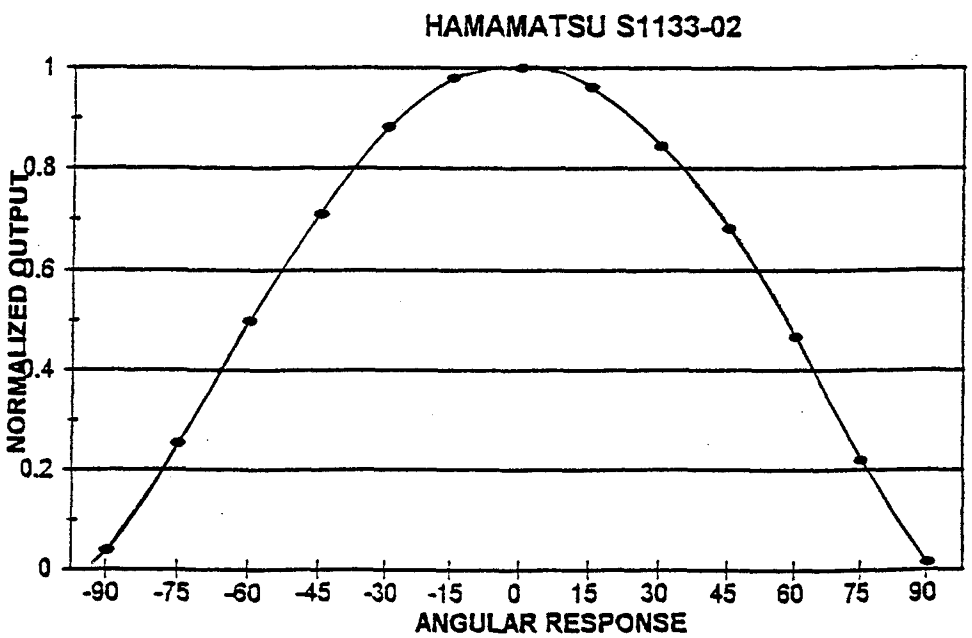


Figure 12. Normalized Angular Response of Hamamatsu S1133-02 Solar Sensor

The black globe radiometer was identified as a known solution to the problem of angular integration of input radiation. However, the standard black globe was too large for use in this application, and miniaturization would be required for use in the EHM sensor suite. This miniaturization activity will be addressed during the second year of this effort.

5. ELECTRONICS

5.1 Sensor Support Module

Two sensor support concepts have been selected for development, each using a modular format. Two such concepts were chosen to accommodate the requirement for globe placement interchangeability and the desire to maintain the option of using either a black globe or a pyranometer type radiation sensor. Each module concept consists of the RH integrated circuit, ambient temperature thermistor sensor, and wind speed thermistor sensor; each incorporates either the miniature black globe thermistor sensor or the miniature pyranometer thermopile. Since the electronics for both modules are essentially identical, recurring design efforts should be minimal to produce the two module types. Figure 13 illustrates the functionality of the sensor support package and secondary radiation sensor option.

Each sensor can be appropriately conditioned to provide a nominal full-scale output voltage for subsequent interfacing to an Analog-to-Digital Converter (ADC), onboard the Data Acquisition System (DAS) control unit. A three-bit identification code originating from the DAS controller provides routing data for the analog multiplexer, which permits polling of any one of six (6) conditioned analog signals. The following outlines the planned sensor suite module specifications:

1. Ambient Temperature: 5 to 65°C, ± 0.6°C
   (Thermistor or RTD or temperature IC Sensor)

2. Relative Humidity: 0 to 100%, ± 4.5%
   (Hy-Cal Sensor)

3. Wind Speed: 0.5 to 4.5 m/s, ±0.5 m/s
   4.5 to 6.5 m/s, ±10%
   (Thermistor Heater/ Sensor)

4. Radiation
   - Black Globe Temperature: 5 to 77°C, ± 0.6°C
     (Thermistor or temperature IC sensor)
   - Pyranometer Range: 0 to 1000 ($\pm$ 150)Watts/m^2,
     suggested sensitivity, (thermopile-type sensor).

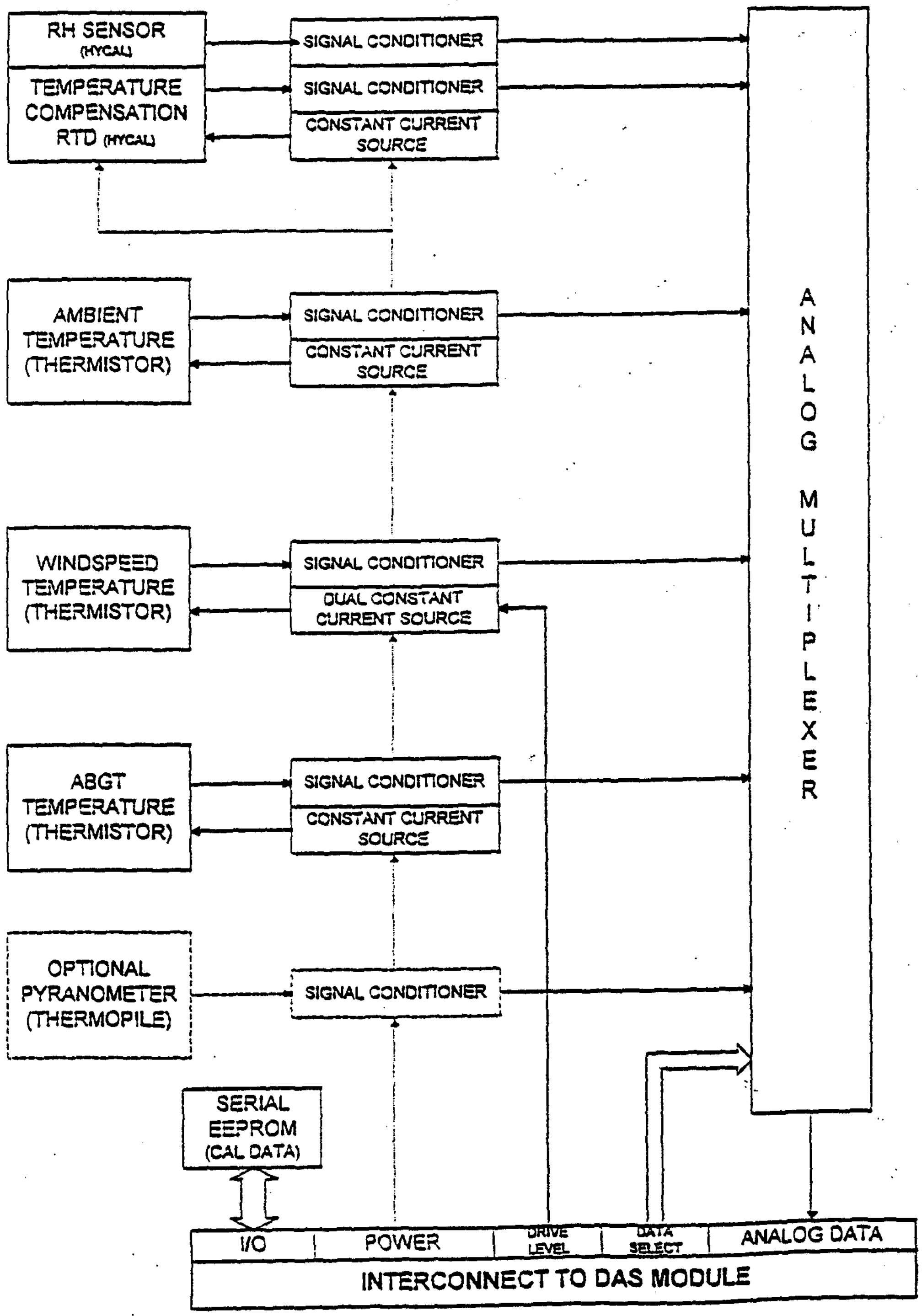


Figure 13. Block Diagram of Sensor Support Module

5.2 System Support Module

It is expected that all functional requirements and sensor module data acquisition needs will be incorporated within the support module section of the instrument. These include:

- Reading user command inputs via multifunction keypad
- Routing and digital conversion of analog sensor data
- Data manipulation and storage
- Remote data communications interface via optical link serial interface
- Display of raw output data via LCD driver module
- Conversion of battery source to regulated power supplies.

5.3 Data Acquisition System (DAS)

The heart of the Data Acquisition System (DAS) instrumentation consists of an 8-bit microcontroller unit (MCU), integrated circuit (IC). Figure 14 illustrates the anticipated architecture, showing peripheral hardware and associated electronics. The Philips Semiconductor 87C576 CMOS microcontroller (or similar derivative of the popular Intel 80C51-based architecture) is expected to be utilized for this function. It was selected as the primary candidate because of its versatility, peripheral support, existing libraries and development software, and future upgradeability. The device's low power consumption is ideally suited for battery-power-dependent instrumentation. It has extensive I/O capability and contains several on-chip features that should effectively reduce the peripheral parts count. For example, it incorporates a 6-channel, 10-bit analog-to-digital converter (ADC) and multiple 16-bit counters, which will be used for data acquisition measurement and sample timing. A built-in Universal Asynchronous Receiver Transmitter (UART) will be used to facilitate serial communications. The on board EPROM (8k) should provide more than ample space for code development, as necessary. Further energy savings may also be realized using the power-down and idle mode feature of the MCU. This essentially shuts down certain functions of the integrated circuit when not in use.

5.4 Display Module

A custom integral LCD driver module and 8-character dot matrix display (not backlit) will be used for outputing data in the form of standard units. The character display area will measure approximately 30mm wide by 5.7mm high.

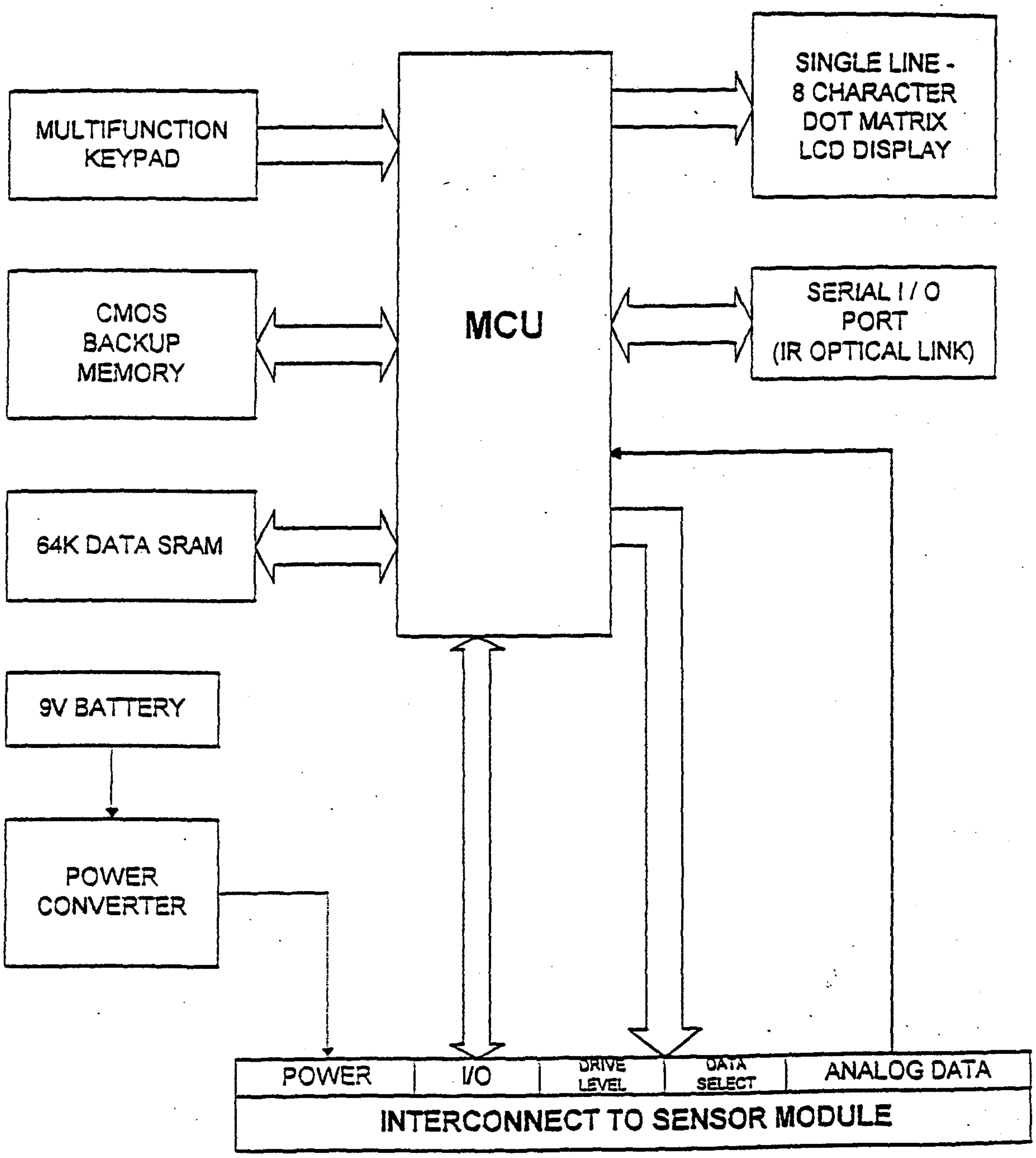


Figure 14. Block Diagram of System Support Module

5.5 Status of Electronics Design and Development

At the contract mid-point, the design of the electronics controller and data acquisition system is still in progress. The portion of the design involving sensor selection is fundamentally completed; however, issues of calibration and control are scheduled to be addressed during the second year of the program.

6. SENSOR MODULES AND SENSOR SUITE EVOLUTION

Several candidate sensor modules and potential sensor suite configurations have been considered. The most promising and innovative were examined to evaluate their respective abilities to address a variety of technical issues of importance (e.g., operation and performance requirements; manufacturing costs and constraints; size, weight, cost, and power objectives, etc.).

6.1 Candidate Module Configurations

6.1.1 Black Globe and Anemometer Module

Conceptually illustrated previously in Figure 9, this candidate sensor module consists of a miniature black globe having a diameter of approximately one inch (25.4 mm). The globe itself is made of thin copper that has been treated with a radiant-energy-absorbing surface coating. A thermistor is placed inside the globe and is used to measure interior temperature. The amount of energy absorbed is a function of the temperature difference between the black globe interior temperature and the ambient temperature.

The black globe is modified by attaching an anemometer hot bead probe on top of the black globe. This can be accomplished either by having a thermally isolated tube placed through the globe or by mounting the anemometer on top of the globe using a thermally insulated connector and having the lead wires go through the globe, exiting at its base. The hot-bead anemometer extends from the top of the globe by approximately 0.125 to 0.25-inch (3 to 6 mm). To minimize wind-flow and temperature-reading interference from the case, this black globe/anemometer module configuration would be located at the end of an arm extending as far as possible from the case.

6.1.2 Ambient Air Temperature and Relative Humidity Probe Module

In this configuration, the ambient temperature and relative humidity (RH) sensors are grouped together in a sensor module (the RH sensor contains an integrated circuit with a temperature sensor). Temperature at the site of the solid-state relative humidity sensor is determined, then the integrated circuit converts the output from the relative humidity sensing element to an analog signal that directly corresponds to the observed

RH. Because of residual heating effects of the instrument upon the air within the RH probe, the true RH value may be in error. Thus, it is desirable to have the ambient air temperature probe sense the air temperature before it enters the RH probe. By correlating ambient air temperature with air temperature within the RH probe, any residual temperature effects can be identified and an accurate RH value can be determined.

6.1.3 Integrated Sphere

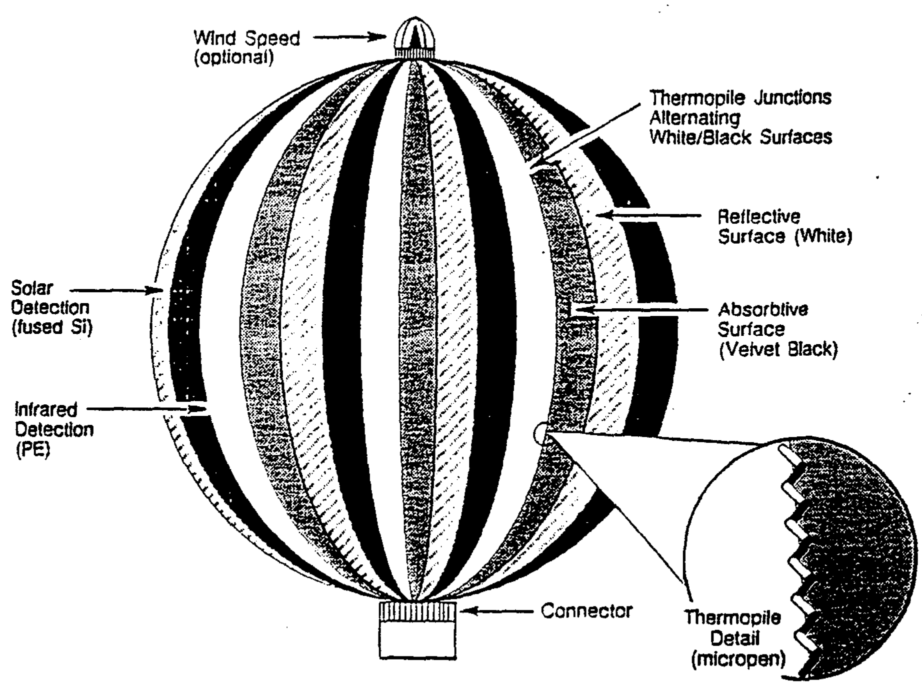
Figure 15 presents a drawing of the candidate integrated sphere concept for achieving omni-directional solar and infrared radiation detection using a one-inch spherical pyranometer made up of a series of black and white bands lying vertical to the plane of the sphere. Each set of white/black bands consists of a single radiant-energy sensor. The temperature difference between the reflecting white band and the absorbing black band can be determined using either an analog (thermopile) or digital (thermistor) measurement of each band. Multiple black and white sensors could be placed on the sphere such that the spherical pyranometer would have an equal sensing area independent of viewing angle.

As shown in Figure 15, the anemometer hot bead would extend from the top of the pyranometer by a small distance [approximately 0.125 to 0.24 inch (3 to 6 mm)]. This would permit wind-speed measurements to be taken with minimal interference. The effect of the spherical substrate underneath the hot-bead anemometer would be minimized by means of calibration techniques.

The ambient temperature sensor and the relative humidity sensor would be placed within the sphere, thereby allowing the sphere to act as a direct radiant energy shield. The bottom and top of the spherical pyranometer would contain openings that would allow for free movement of ambient air within the sphere. If the interior of the spherical pyranometer were not used as a direct radiant energy shield (and another technique were substituted for this purpose), then the ambient air temperature and relative humidity sensors could be housed in the support stem that holds the pyranometer/anemometer away from the sensor suite case.

While this innovative, fully integrated approach to sensor suite design appears to be a technically viable concept, both preliminary analysis and discussions with potential manufacturers have led to the conclusion that the cost of developing and validating this particular sensor configuration is beyond the scope and funding levels of the Phase II SBIR program.

INTEGRATED CONCEPT
(Omni Directional Solar/Infrared Detector)



6.2 Candidate Sensor Suite Configurations

Several candidate configurations were devised for integrating the various sensor elements into a single package meeting the size, weight, cost, and power constraints. System size and power reductions were taken as primary objectives, generating an evolutionary movement toward a cigarette-pack-sized exterior case. Figures 16 through 19 provide conceptual drawings of concepts considered and rejected.

Figures 16 and 17 depict potential volt-meter-sized configurations. Figures 18 and 19 picture "flashlight/torch" and "slide storage," configurations, respectively. These candidate configurations were rejected in favor of a smaller, cigarette-pack-sized configuration that incorporates easily replaceable parts, state-of-the-art electronics and sensor technologies, and integrated sensor modules.

Shown in both open and closed modes in Figure 20, the configuration selected for fabrication, test, and validation during the second year of this program features two of the integrated sensor combinations discussed earlier: (1) the black globe/anemometer module and (2) the ambient temperature sensor/relative humidity sensor module.

To achieve minimal case and inter-sensor interference effects as well as easy replacement of a malfunctioning part, the radiation sensor/anemometer module has been placed on the end of an extending arm. Similarly, the ambient temperature/relative humidity sensor has been placed within an extension arm. Alternatively, this module could be attached to the case containing the supporting electronics, display, RS232 port and battery.

Taking maximum advantage of state-of-the-art chip technology, it is possible to use three printed circuit boards within the unit. The extension arm houses the signal conditioning electronics; the output of this board is an analog signal proportional to the sensor value. One board is used to support the display mounted on the surface of the sensor suite case; another is used to contain all support electronics (including the system controller, data link port, and the data acquisition system). The suite will be equipped with an infrared optical RS232 port that will allow the data obtained to be transferred on command to a remote location (such as a computer or a data logger).

Each sensor module contains all the conditioning electronics needed to power the individual sensors, as well as the signal-conditioning electronics required to generate an analog signal with a full range from 0 to 5 V DC. This approach has the following advantages:

- The data acquisition system is required to read only one analog output (in the 0 to 5 V DC range);

INTEGRATED CONCEPT

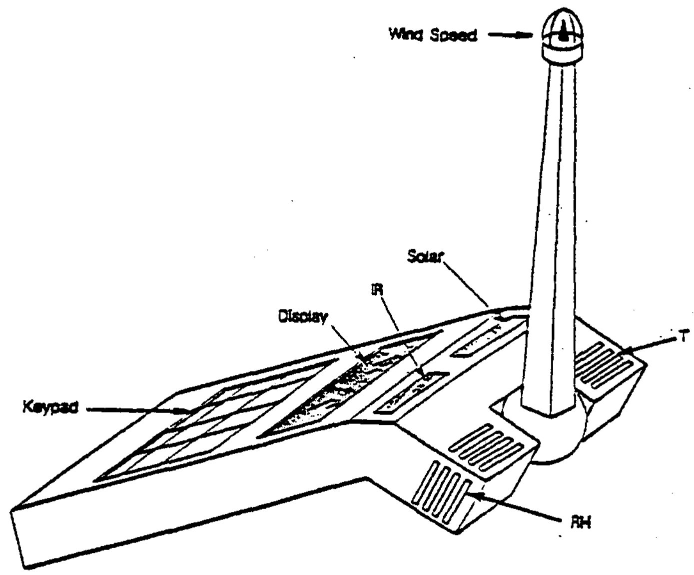


Figure 16. Voltmeter with Bent Case

INTEGRATED CONCEPT

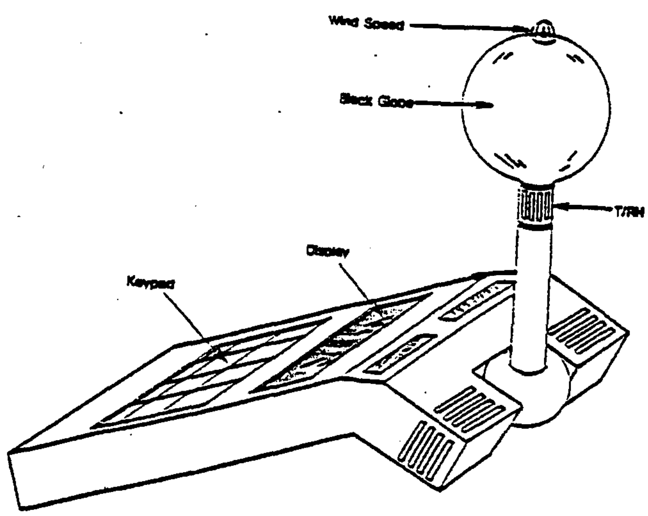


Figure 17. Multi-Sensor

INTEGRATED CONCEPT
(Flashlight/Torch)

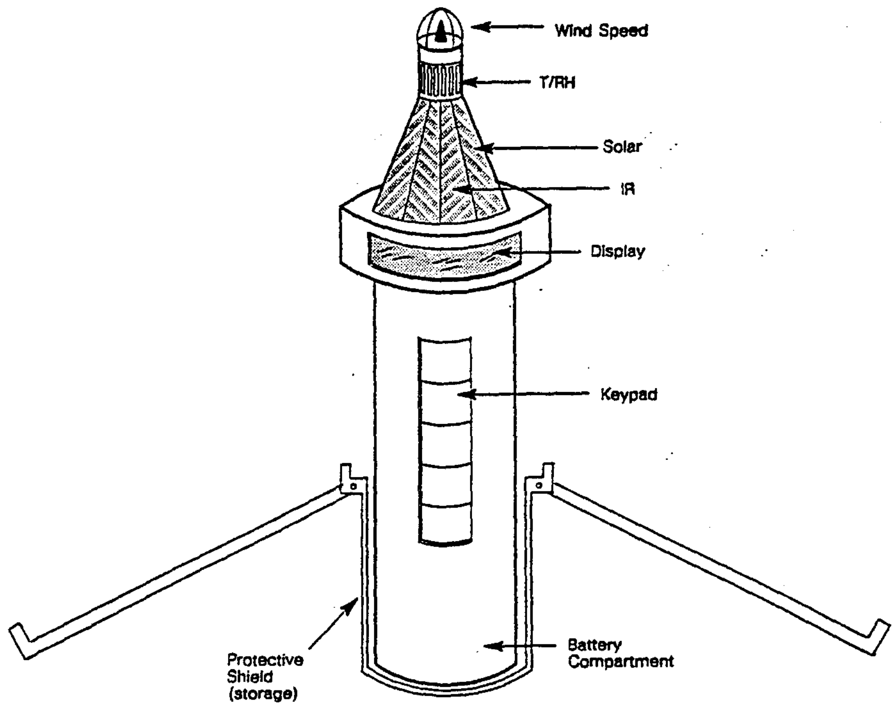


Figure 18. Flashlight Torch

INTEGRATED CONCEPT
(Slide Storage)

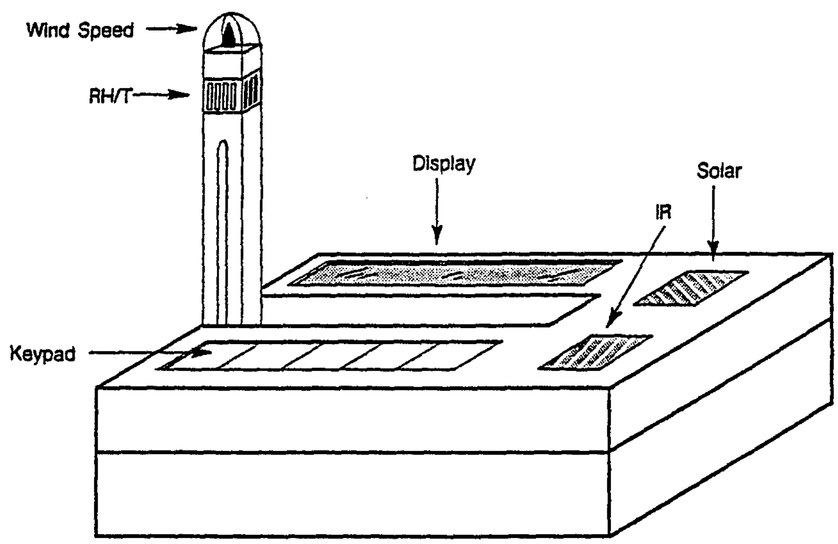


Figure 19. Slide Storage

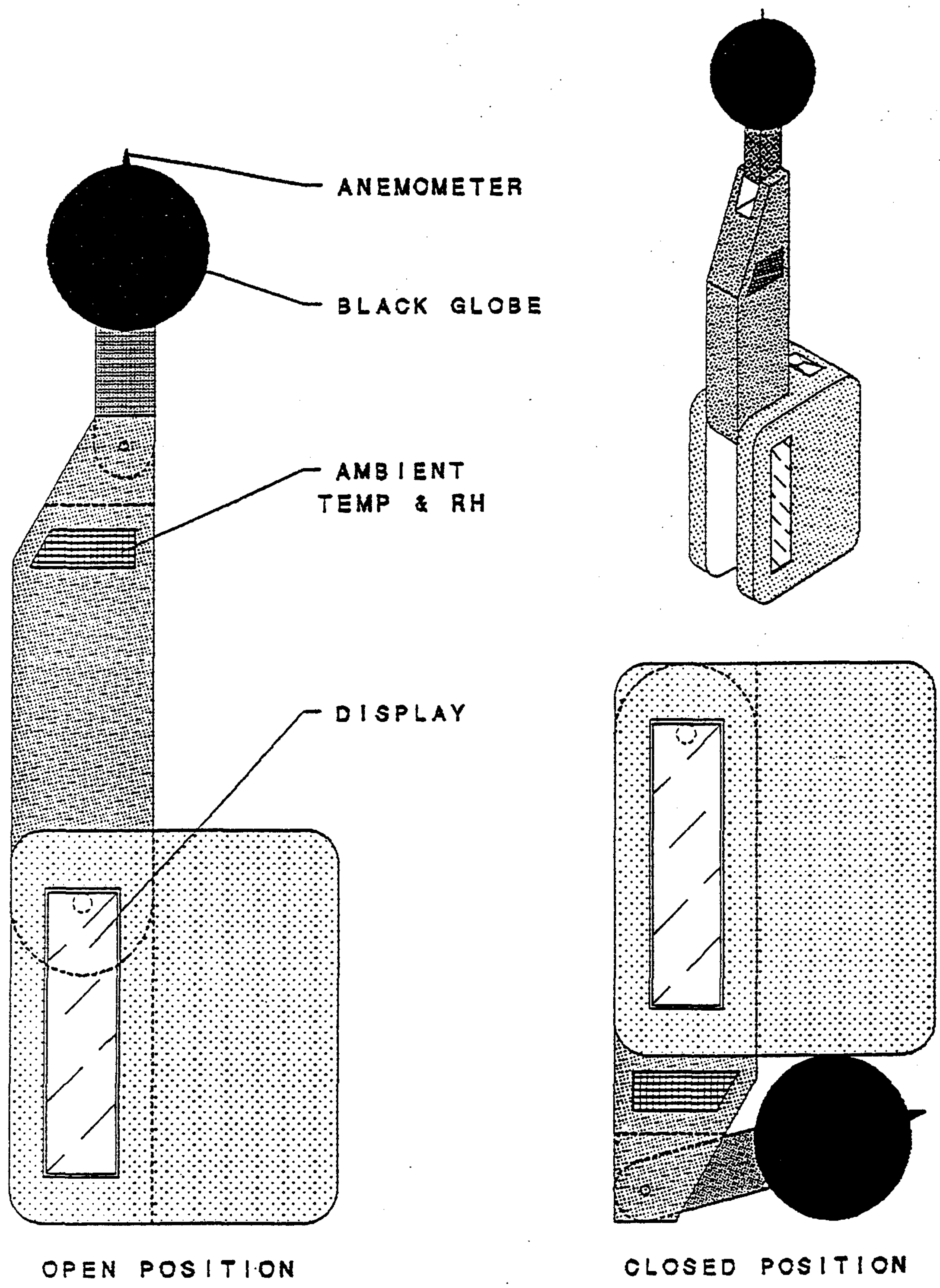


Figure 20. Cigarette Pack Sized Configuration

- Each sensor module is pre-calibrated (permitting sensor upgrade, or the addition/deletion of various sensor modules, depending on specific application).

The electronic support system contains a system controller that monitors all functions and maintains effective internal communications links. The data acquisition system has the ability to store a limited amount of data runs (storage capacity is dependent on the length of the data train and the amount of memory available). As a minimum, one complete data set can be stored. If memory space is available, additional data sets can be stored for later downloading to larger storage devices.

Power will be supplied by a 9-Volt, DC conventional alkaline battery, which will permit a sufficient duty cycle to operate effectively over a military mission time of 72 hours.

The suite will be provided with a three-function, membrane keypad. The first function will turn the suite on or off. Each time the system is turned on, it will perform a built-in-test (BIT) to determine that electronics components and the battery are functional. The second function will start a data run. The start sequence will first perform a BIT to indicate all systems are functional, then initiate the system controller to start a data run to obtain the environmental parameter values, and store them in memory. The purpose of the third function is to display the observed data set so that the local operator can obtain the environmental parameter data by scrolling each of the environmental parameters: ambient temperature, relative humidity, wind speed, and radiant energy.

The case design is still under consideration.

7. CONCLUSIONS

The following points are conclusions based on the first year of the program:

- Sensor technology is adequately developed to permit a miniaturized sensor suite to be configured and packaged at the target size (approximately the size of a cigarette package).

- Neither the sensor suite's size nor its weight pose an unacceptable burden; the sensor suite as presently configured should not interfere with mission objectives or activities.

- Both sensor suite size and downloading capability indicate that the suite can be networked via radio link (SINGARS) for use in mission planning.

- Sensors can be integrated into modules to minimize space requirements and to prevent interference among sensor functions.

- Sensor module integration minimizes cost and facilitates maintenance and logistics since it will be possible to replace broken modules (rather than the entire unit).

- Sensor module electronic design allows for one-to-one replacement; there will be no need for re-calibration at either the soldier or the depot level.

- Using currently available chip technology, the electronics needed to support sensor operation, data recording and display, and data linking (via RS232 port) can be fit within the constraints of the size and weight objectives.

- The sensor suite is suitable for dual-purpose usage, satisfying the needs of both military and civilian applications.

The following conclusions were reached concerning the sensor technology:

- Test results indicate that a pulsed anemometer can be successfully integrated into the suite.

- The radiant energy measurement can be performed using a miniature black globe having sufficient accuracy for the subject application.

- Size and power demand reductions are achievable.

- Miniaturized relative humidity sensors are available off-the-shelf; these sensors, which generate RH output directly as an analog signal, contain dedicated integrated circuits and are temperature controlled and precalibrated.

By combining current sensor technology and state-of-the-art electronic chip technology, it will be possible to package a compact, lightweight, and relatively inexpensive temperature sensor suite in a physical configuration that approximates the size of a cigarette package. The work conducted during the first year of this two-year program has provided a more than adequate foundation to support breadboard fabrication and performance testing of subsystem performance, followed by fabrication and validation of a prototype unit.

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APPENDIX A. LITERATURE REVIEW: SENSOR TECHNOLOGY

ADVANTAGES AND DISADVANTAGES OF VARIOUS SENSOR TECHNOLOGIES AS APPLIED TO THE SUBJECT SENSOR SUITE

SENSOR: Wind Speed

TECHNOLOGY	ADVANTAGES	DISADVANTAGES
1. Hot Wire (Constant Temperature) or Hot Film	1.1 Small 1.2 Sensitivity and resolution 1.3 Hot-film on a conical substrate generates an omni-directional sensor.	1.1 Requires a large power drain to maintain the hot wire at an elevated temperature for 3 minutes. 1.2 For increased accuracy and resolution, moisture content (grams of water vapor/cc) is required to perform heat transfer calculations. 1.3 Not omni-directional as hotwire.
2. Hot Wire (Pulsed) or Hot Film	2.1 Small 2.2 Does not require large power drain. The hotwire element is heated with a given amount of energy. A measurement is made of the temperature that the hot wire reaches and the rate that the hotwire elements cools. The combination of these two data points can be used to calculate the wind speed based upon heat transfer calculation.	2.1 Requires S/W development. 2.2 Technique has not been used in the past. It must be proven and validated. 2.3 Sensitivity, resolutions and accuracy are unknown.
3. Impeller	3.1 Small unit 3.2 Requires little power demand.	3.1 Mechanical device may not be good at low wind speed due to friction. 3.2 Not omni-directional. Requires two at right angles and use vectoring to determine wind speed.

ADVANTAGES AND DISADVANTAGES OF VARIOUS SENSOR TECHNOLOGIES AS APPLIED TO THE SUBJECT SENSOR SUITE

SENSOR: Wind (Con't)

TECHNOLOGY	ADVANTAGES	DISADVANTAGES
4. Rotating Cup	4.1 Mechanical 4.2 Hardened instrumentation 4.3 Requires minimal power. 4.4 Omni-directional	4.1 Cup arms may be fragile. 4.2 Low speed limitations 4.3 Maintenance to keep the cup/vane mechanism free to rotate.

ADVANTAGES AND DISADVANTAGES OF VARIOUS SENSOR TECHNOLOGIES AS APPLIED TO THE SUBJECT SENSOR SUITE

SENSOR: Temperature

TECHNOLOGY	ADVANTAGES	DISADVANTAGES
1. Thermocouple/thermopile	1.1 Miniature size 1.2 Does not require power to measure temperature	1.1 A very small electrical signal is generated. The resultant amplification generates a very poor S/N level. This may be overcome by using a multiple of thermocouples in series: called a thermopile. 1.2 Requires a reference temperature junction referred to as the cold junction.
2. Thermistor	2.1 Miniature size 2.2 Good S/N level of output of thermistor 2.3 Can be precalibrated to +/- 0.1 °C	2.1 Fragile and must be protected from physical harm and rough handling.
3. Liquid Thermometer	3.1 None	3.1 Optical viewing required with no electrical feedback for datalogger. 3.2 Low resolution 3.3 Fragile unit

ADVANTAGES AND DISADVANTAGES OF VARIOUS SENSOR TECHNOLOGIES AS APPLIED TO THE SUBJECT SENSOR SUITE

SENSOR: Relative Humidity

TECHNOLOGY	ADVANTAGES	DISADVANTAGES
1. Dew Point - Mirror Device	1.1 Very accurate and precise data on the measurement of dew point. This, with the ambient DB temperature, will give relative humidity.	1.1 Large size. The unit can not be miniaturized. 1.2 Large power drain to constantly chill the mirror and operate the optical sensing detector. 1.3 High cost of supporting electronics.
2. Wet Bulb	2.1 Can be used for both non-aspirated (natural) relative humidity or aspirated relative humidity.	2.1 Requires a wetted wick around one of the temperature probes. This generates a requirement for a fresh water reservoir to be with the RH probe. 2.2 Aspirated RH probe requires that air be drawn over the wetted probe at a speed greater than 3+ MPH. This generates a power demand that is large for a long sampling period. 2.3 The wick material becomes contaminated with atmospheric salts and salts in the water supply. This effects the evaporation rate of the wick which results in a false reading.
3. Capacitor Devices	3.1 Small miniature size 3.2 Very little power drain 3.3 Covers a wide range of RH by measuring absolute humidity or water content in a polymer film that is at equilibrium with the surrounding air vapor content. 3.4 Field hardened OTS devices 3.5 Have built in IC units for signal processing.	3.1 Time constant may be slow due to equilibrium between the air and the reactive polymer film. 3.2 Hysterisis effect may exist to generate some measurement error.

ADVANTAGES AND DISADVANTAGES OF VARIOUS SENSOR TECHNOLOGIES AS APPLIED TO THE SUBJECT SENSOR SUITE

SENSOR: Relative Humidity (Con't)

TECHNOLOGY	ADVANTAGES	DISADVANTAGES
4. Differential cooling of heated thermistors	4.1 Small 4.2 Calibrated to give absolute water vapor content in air. 4.3 Field hardened 4.4 Hybrid Integrated Chip (HIC) has been built that controls the heating, monitoring the cooling of the two thermistors, and the generation of the analog signal for a data logger. 4.5 Comes with a metal , PE, or metal+PE porous protective shield.	4.1 Requires power to heat thermistor to a temperature significantly above ambient air temperature such that the cooling rate can be measured.

ADVANTAGES AND DISADVANTAGES OF VARIOUS SENSOR TECHNOLOGIES AS APPLIED TO THE SUBJECT SENSOR SUITE

SENSOR: Solar/Radiant

TECHNOLOGY	ADVANTAGES	DISADVANTAGES
1. Differential Energy Absorption: Star, concentric circles or stripped pattern of alternating white and black coated metal substrate connected by thermocouples forming a thermopile (pyranometer)	1.1 Wide viewing angle 1.2 Simplicity of measurement. Ambient air temperature is compensated for by measurement technique. One part of the thermocouple is painted black and the other side is painted white. The radiation will reflect from the white piece and absorb on the black piece. Thus the temperature difference is the result of the absorbed radiation and independent of ambient air temperature. 1.3 The detector scheme is a series of thermocouples that form a thermopile to give adequate S/N level. 1.4 Compensates for self-heating due to black body radiation.	1.1 Observation solid angle is governed by Lambert's cosine law. Thus viewing angle from side is very small compared to direct viewing 1.2 Requires bandpass filters to allow only solar (glass) or near infrared (PE) to be measured.
2. Total Energy Absorption Sensor	2.1 Small size of sensor. Can be the size of a TO-5 can or about 10 mm diameters. 2.2 Ambient air temperature compensated. 2.3 Compensates for self-heating due to black body radiation.	2.1 Has a limited viewing angle of less than 120° 2.2 Requires a bandpass filter or transparent cover over opening in the TO-5 tin 2.3 Large S/N due to thermocouple

ADVANTAGES AND DISADVANTAGES OF VARIOUS SENSOR TECHNOLOGIES AS APPLIED TO THE SUBJECT SENSOR SUITE

SENSOR: Solar/Radiant (Con't)

TECHNOLOGY	ADVANTAGES	DISADVANTAGES
3. Black Globe	3.1 Integrates radiant/solar energy. 3.2 Considers wind convective cooling (correlates with man).	3.1 Very slow time constant to come to equilibrium . 3.2 Does not differentiate between solar and radiant energy.

APPENDIX B. SENSORS/ELEMENTS RECOMMENDED FOR EVALUATION AND SOURCES OF COMMERCIALLY AVAILABLE SENSOR TECHNOLOGY

RECOMMENDED SENSOR ELEMENTS FOR EVALUATION

PARAMETER	TECHNOLOGY	SENSOR/MANUFACTURER
Temperature	Thermistor	Multi-sources
Wind Speed	Mechanical Hot bead Hot wire Differential Cooling	Testoterm Sierra, Testoterm,Dantec Cole-Parmer Custom fabricated [Micropen]*
Humidity	Differential Cooling Thin Film Cap. Resistive Polymer Film	Shibaura Panametrics, HYCAL, Elan, Omic Victory Engineering
Black Globe Probe [Integrated Solar/Rad]	Black Globe Thermometer	IST
Solar (0.4 to 0.8µ) Filter: 0.4 to 2µ	Thermopile Photocell	Armtec Hamamatsu, Victory Eng.
Radiant (8 to 14µ) Filter: 2 to 20µ	Thermopile Photocell	Armtec Hamamatsu

* Requires significant Research and Development

COMMERCIAL SOURCES FOR RECOMMENDED SENSORS/ELEMENTS

RH	WS	S	R	BGT	Name	Telephone No
X	X				Alnor	708.677.3500
X					Analite Incorporated	516.752.1818
		X	X		AMP	215.666.3500
X					AMETEK	302.456.4400
	X				Applied Technologies, Inc.	303.530.4977
		X	X		Armtec Industries Inc	603.669.0940
X	X				Barnant	800.637.3739
				X	Bruel & Kjaer	513.753.1657
		X	X		Centronic	805.499.5902
X	X				Climatronics Corp	516.567.7300
	X				Climet Instruments	909.793.2788
X	X				Cole-Palmer	800.323.4340
	X				Dantec Measuremet Tech	201.512.0037
X	X			X	Davis Instruments	800.368.2516
X					Elan Technical Corp	203.335.2115
X	X				Earth and Atmospheric Sci	800.543.9930
X					EG&G	617.270.9100
		X	X		Eplab Laboratory	401.847.1031
X					Extech Instruments	617.890.7440
X					General Eastern	800.225.3208
	X				Gardco	305.946.9454
		X	X		Hamamatsu	908.231.0960
	X				Honeywell-Microswitch	800.537.6945
X		X	X		HY-CAL	818.444-4000
X	X			X	IST	716.266.9003
X	X	X	X	X	Kahl Scientific Inst	619.444.0207
X					Kahn	203.529.8643

COMMERCIAL SOURCES FOR RECOMMENDED SENSORS/ELEMENTS

RH	WS	S	R	BGT	Name		Telephone No
X					Leeds and Northrup		215.699.2000
		X	X		Li-COR		402.467.3576
X					Newport Scientific, Inc		301.496.6700
X		X	X		Omega		800.826.6342
X					Ohmic Instruments		800.626.7713
	X				Ohmcraft (Micropen)		716.586.0823
		X	X		Optronics Laboratories, inc		407.422.3171
X	X				Pacer		800.283.1141
X					Panametrics		617.899.2719
X					Phys-Chem Scientific Corp		212.924.2070
X					Protimeter		516.864.5643
X	X				Qualimetrics		916.928.1000
X	X				Shibaura Electronics	Tel	048.852.6661 (Japan)
						Fax	048.852.4324 (Japan)
	X				Simerl Instruments		410.849.2505
	X				Sierra Instruments		800.866.0200
X	X				Solomat		203.849.3111
X					Taylor Environmental Inst		704.684.5178
X					Tescp International		415.572.1683
X	X				Testoterm, Inc		800.227.0729
X					Thunder Scientific Corp		800.872.7728
	X				TSI		800.TSI.2811
X					Vaisala		617.933.4500
X					Victory Engineering		201.379.5900

DEPARTMENT OF THE ARMY
US ARMY MEDICAL RESEARCH AND MATERIEL COMMAND
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DAMD17-94-C-4026	ADB187918
~~DAMD17-94-J-4250~~	~~ADB221970~~
~~DAMD17-94-J-4250~~	~~ADB230700~~
DAMD17-96-1-6241	ADB233224
DAMD17-96-1-6241	ADB218632
DAMD17-94-J-4496	ADB225269
DAMD17-94-J-4392	ADB225308
DAMD17-94-J-4455	ADB225784
DAMD17-94-J-4309	ADB228198
DAMD17-91-C-1135	ADB233658
DAMD17-94-J-4038	ADB232313
DAMD17-94-J-4073	ADB222794
DAMD17-94-J-4131	ADB219168
DAMD17-94-J-4159	ADB232305
MIPR 95MM5535	ADB232218
95MM5605	ADB233374
95MM5673	ADB226037

MCMR-RMI-S
SUBJECT: Request Change in Distribution Statement

2. Point of contact for this request is Ms. Judy Pawlus at DSN 343-7322 or email: judy_pawlus@ftdetrck-ccmail.army.mil.

FOR THE COMMANDER:

Phylis Rinehart

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